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UNMANNED SURFACE COMBATANT
Considerations for Concept Exploration

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June 2011

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ABSTRACT

This capstone project explored the operational and design considerations/constraints for an autonomous Unmanned Surface Combatant (USC). Using a USC in selected missions could lead to cost reductions and enhanced capabilities when compared with similar manned combatants by eliminating personnel and automating ship operations. Operations and Support (O&S) costs, which include personnel costs, are a large portion of the Navy's total ownership costs (TOC) for surface combatants, and can be as high as 38 percent of the TOC [Elmendorf, 2010]. Enhanced capabilities for a USC could be derived from performing operational activities manned ships cannot; and automated tasks could be performed more efficiently and effectively by a computer system than a human. A modified waterfall systems engineering process model was used to explore a USC concept. A needs analysis was performed, and mine warfare and anti-submarine warfare were identified as appropriate military missions for an initial USC concept. Top level constraints for a USC concept and support missions were developed. Design considerations, relevant technologies, and concept risks were investigated. This capstone project concluded that a lower cost, higher capability autonomous USC is possible based on the current state of relevant technologies. However there are significant technical challenges to overcome before full autonomy is possible. Further, more rigorous design studies are recommended.

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The project team takes pride in the knowledge that this report could aid further work in the field of autonomous surface combatants for the US Navy.

Most importantly, the team would also like to thank our families who have supported us through the Capstone project and the Master's program for the past two years.

LIST OF ABBREVIATIONS AND ACRONYMS

4C	Central Control Computing Center
ABS	American Bureau of Shipping
AFFF	Aqueous Film Forming Foams
AI	Artificial Intelligence
AIS	Automatic Information System
AMR	Auxiliary Machinery Room
A_o	Operational Availability
ARCI	Advanced Rapid COTS Insertion
ASW	Anti Submarine Warfare
C2	Command And Control
C3	Command, Control, and Communication
C4ISR	Command, Control, And Communications Information, Surveillance, And Reconnaissance
CBR	Chemical, Biological, Radiological
CEC	Cooperative Engagement Capability
CIWS	Close-In Weapons System
COLREGS	International Regulations for Preventing Collisions at Sea
CONOPS	Concept of Operations
COTS	Commercial Off The Shelf
CPP	Controllable Pitch Propeller
CSG	Carrier Strike Group
DEFCON	Defense Readiness Condition
DOD	Department of Defense
DON	Department of the Navy
ECM	Electronic Counter Measures
EO/IR	Electro Optics/Infrared
ERAD	Extended Range Acoustic Device
ESG	Expeditionary Strike Group

ESM	Electronic Support Measures
EW	Electronic Warfare
FEDS	Full Engagement Demonstration Simulation
FLIR	Forward Looking InfraRed
GCCS-M	Global Command and Control System - Maritime
GPS	Global Positioning System
GRP	Glass-fiber Reinforced Plastic
HAUV	Hovering Autonomous Underwater Vehicle
HFP	Hexafluoropropylene
IFF	Identification, Friend or Foe
ISR	Intelligence, Surveillance, and Reconnaissance
LAN	Local Area Network
LANT	Atlantic Fleet
LCS	Littoral Combat Ship
LIDAR	Light Detection And Ranging
LRAD	Long Range Acoustic Device
MAD	Magnetic Anomaly Detection
MCM	Mine Counter Measure
MIW	Mine Warfare
MMR	Main Machinery Room
MNS	Mission Needs Statement
MOE	Measures of Effectiveness
MOP	Measures of Performance
NAV	Navigation
NAVSEA	Naval Sea Systems Command
NGIPS	Next Generation Integrated Power System
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Center
O&S	Operations and Support
ONR	Office of Naval Research
OPAREA	Operations Area

OPNAVINST	Chief of Naval Operations Instruction
OPSEC	Operations Security
PAC	Pacific Fleet
PDA	Primary Damage Area
PEO	Program Executive Office
PKP	Potassium Bicarbonate (aka Purple-K-Powder)
PMS	Preventative Maintenance System
QDR	Quadrennial Defense Review
R&D	Research and Development
RBOC	Rapid Blooming Offboard Chaff
REMUS	Remote Environmental Measuring UnitS
RF	Radio Frequency
RMS	Remote Minehunting System
SATCOM	Satellite Communication
SG	Strike Group
SM	Standard Missile
SMCM	Surface Mine Countermeasures
SSDS	Ship Self Defense System
SSN	Fast Attack Submarine
TACTAS	Tactical Towed Array Sonar
TEWA	Threat Evaluation and Weapon Assignment
TSCE	Total Ship Computing Environment
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UISS	Unmanned Influence Sweep System
US3	Unmanned Surface Sweep System
USC	Unmanned Surface Combatant
USN	United States Navy
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
VAMOSC	Visibility and Management of Operating and Support Cost

VDS	Variable Depth Sonar
VTUAV	Vertical Take-Off and Landing Tactical Unmanned Aerial Vehicle

Executive Summary

Operations and Support (O&S) costs, which include personnel for a ship over its life cycle, account for a large portion of the Navy's total ownership costs (TOC) for surface combatants, and can be as high as 38 percent of the TOC [Elmendorf, 2010] . The use of Unmanned Surface Combatants (USCs) would reduce personnel costs for ships. A USC offers other advantages including the elimination of many habitability systems and human interface features that are necessary on manned ships. By eliminating these design features and their requisite space, weight, and power requirements, the ship design trade space could achieve more flexibility enabling an increase in speed, payload, and range or a decrease in ship size to further reduce total ownership costs. Most importantly, an autonomous USC offers many operational advantages over a manned equivalent.

Autonomous unmanned systems may be better suited than a manned alternative for certain operations that can be considered too dull, dirty, or dangerous for humans to perform effectively or efficiently. As the capabilities of the automated systems improve, an unmanned ship could perform these actions as well as routine actions such as navigation more effectively.

An objective of this project was to explore the concept of an autonomous unmanned surface combatant and identify the operational and design constraints, design considerations, and explore the relevant technologies that would enable a USC to replace a manned surface combatant for some missions.

A modified waterfall system engineering process model with steps that included Needs Analysis, Operational Analysis, Functional Analysis, Concept Discussion, and Final Analysis was used to formulate the USC concept considerations. Using interested party survey inputs and a needs analysis, which highlighted the potential benefits of leveraging autonomous unmanned operations for certain missions, the team chose Anti-Submarine

Warfare (ASW) and Mine Warfare (MIW) as the two primary missions to explore. Both of these missions generally involve an extensive search of large areas looking for small signature targets. Several other mission areas identified in the needs analysis, such as Mobility and Command, Control, and Communication (C3), are required regardless of the missions a USC would perform so these mission areas were included in the concept exploration as well.

A concept of operations (CONOPS) and high level constraints were developed to help identify operational activities. Following this, seven USC functions were identified as ASW, MIW, C3, Navigation, Self-Defense, Damage Control, and Machinery. A functional allocation was then performed which allocated the low level operational activities to the USC subsystems and components. This allocation helped identify what relevant technologies a USC would require to accomplish ASW and MIW as well as the general ship functions. The functional architecture was tracked in CORE® 7.0 during the entire concept exploration process.

While there may be many benefits of a USC, the unmanned and autonomous nature of the ship presents unique challenges and potential problems. The ship will be capable of self-defense and prosecution of submarines. These actions may result in the firing of a weapon that can cause loss of life. The USN currently relies on an individual who has ultimate responsibility for the consequences. The USC will rely on a computer program to evaluate the need for and the authorization of weapons release in the case of self defense and it is expected that initially, weapon firing upon manned assets may have to be authorized by a human.

MIW and ASW lend themselves to unmanned operation, and there are many technologies which are close to full autonomy. Investments in software are required to get many systems over the last hurdles, and in some cases, mechanical adaptation will also need to occur. Once these targeted investments have been made, there is a real potential for significant life cycle cost savings in both acquisition and O&S for the USC as compared to a manned surface combatant.

I. INTRODUCTION

The introduction section of this report presents the project team and the problem statement for the report. An expanded project background and report objectives are also presented along with the systems engineering process model the team used to address the problem statement.

A. CAPSTONE PROJECT TEAM

The capstone project team was composed of 6 members of the NAVSEA Carderock/Newport Cohort 311-094.

- Patrick Cox – NSWC Carderock, Code 6102
- Christie Jordan – SUPSHIP Bath, Code 153T1
- Kate Mangum – NSWC Carderock, Code 5300
- John Mitchell – NSWC Carderock, Code 2410
- Kevin O'Neill – NSWC Carderock, Code 711
- Kevin Seraile – NSWC Carderock, Code 732

Five of the team members work in the Washington, DC area for organizations that include NSWC Carderock, NAVSEA 05, and OPNAV. The sixth team member works for the Supervisor of Shipbuilding in Bath, Maine. The project lead role was rotated among team members with Patrick Cox and Kate Mangum taking prominent roles. At the project inception, the team had little knowledge and no expertise of the capabilities, missions, mission equipment, and ship design that would be necessary to identify a concept design for an autonomous Unmanned Surface Combatant (USC). Many of the capstone project deliverables such as the Concept of Operations (CONOPS), Project Management Plan, and project schedule were team efforts. The team divided into functional areas to research technologies and systems required not only for systems necessary for combatant operations but also for the technologies and designs that would enable autonomous unmanned ship operation. Patrick Cox led the CORE modeling and Requirements research. Christie Jordan led the Damage Control, Self-Defense, and cost analysis research, Kate Mangum led the MIW (Mine Warfare) and System Integration research, John Mitchell led the Top Level Physical Architecture and Machinery research, Kevin O'Neill

led the USC Central Control Architecture research, and Kevin Seraile led the Anti-Submarine Warfare (ASW) and Navigation research.

B. PROBLEM STATEMENT

The objective of this project was to explore the concept of an autonomous USC and identify the design considerations, design constraints, and relevant technologies that would enable the United States Navy (USN) to build and incorporate a USC into naval operations. Both current and developmental technologies that enable a USC concept have been investigated. The goal of the USC concept is to achieve full autonomous capabilities to satisfy mission requirements.

Studies aimed at significantly reducing or eliminating manning have concluded that some degree of manning is necessary[Erwin, 2008]. The notion of required manning is rooted in years of culture; legal, ethical, and political reasons; and safety [Canning, 2009]. As a result studies with a true “out of the box” approach to achieving a USC have not been previously attempted by the Navy. All of the studies investigated to date have examined boats usually of 11m or less in length, none have addressed a USC.

C. BACKGROUND

Operations and Support (O&S) costs are a large portion of the Navy’s total ownership costs for today’s surface combatants. O&S costs include both personnel and maintenance for a ship over its total life cycle. Surface combatants are expected to have a service life of 25 to 35 years and personnel costs can be as high as 38 percent of the total life cycle cost [Elmendorf, 2010]. According to an April 2008 article in National Defense, the expense of recruiting, retaining, training and providing medical benefits for service members and retirees is growing faster than anyone had predicted. Even though the Navy is eliminating people from the ranks, its personnel costs still are expected to rise by 5 percent a year [Erwin, 2010].

Recent programs such as the Littoral Combat Ship (LCS) and the DDG 1000 have attempted to reduce their manning requirements, which translates to reduced O & S cost, with mixed results. LCS is estimated to still have approximately 15 percent of the total ownership cost as personnel

costs [Elmendorf, 2010]. Even with this reduced manning, the personnel cost is estimated to be $161M per ship (life cycle) for the LCS-1 and LCS-2 [Elmendorf, 2010].

A completely unmanned surface combatant offers expanded operational advantages including the elimination of many human habitability systems and interface features such as operator consoles, berthing, lounges, mess rooms, offices, medical spaces, and galleys that are necessary on manned ships. By eliminating these features and their requisite space, weight, and power requirements, the ship design trade space could achieve more flexibility enabling an increase in speed, payload, and range or a decrease in ship size to further reduce total ownership costs.

Most importantly an autonomous USC offers many potential operational advantages over a manned equivalent. Autonomous unmanned systems may be better suited than a manned alternative for certain operations that can be considered too dull, dirty, or dangerous for humans to perform effectively or efficiently. As the capabilities of the automated systems improve, unmanned ships could perform these actions as well as routine actions such as Navigation more effectively.

An unmanned system is also less susceptible to environmental and man-made hazards than a manned alternative. An autonomous USC could enter operational areas whose environments are too extreme for a manned ship to enter. For example, the USC would be able to enter toxic or radioactive areas to gather intelligence. A USC would be ideally suited for an environment that would be potentially deadly for personnel onboard a manned ship and would keep sailors out of harm’s way.

Operations where vigilance is paramount, such as area monitoring, may be better performed by autonomous unmanned systems. The autonomous system can be present in areas longer and maintain the monitoring operation at a higher fidelity than human counterparts who become fatigued. The USC systems could perform missions without having to consider the health and morale of the crew.

Arguably the most valuable benefit to having an unmanned USC may be removing USN personnel from dangerous situations. Even beyond specific operations, an unmanned surface combatant shifts the paradigm of naval operations. Instead of being risk averse to prevent loss of life, the Navy can use the USC in higher risk ways because the consequence of damage or destruction is much less severe than using a manned alternative.

While there may be many benefits of a USC, the unmanned and autonomous nature of the ship presents unique challenges and potential problems. The ship will be capable of self-defense and prosecution of submarines. These actions may result in the firing of a weapon that can cause loss of life. The USN currently relies on an individual who has ultimate responsibility for the consequences. The USC will rely on a computer program to evaluate the need for and the authorization of weapons release in the case of self defense and it is expected that initially, weapon firing upon manned assets will have to be authorized by a human. Unless there is real-time monitoring of the USC sensors and situation, using the ship as part of a shield may introduce latencies that affect the safety of the defended asset. Using a computer to fill the human role will require programming that is able to process and react to every situation with complete confidence that the proper action is taken. The USC also introduces a "fear of the unknown" factor in its operation to both adversaries and allies alike. Operating around a relatively large unmanned ship will present operational challenges for the other ships until the USC is proved capable of safe operation. Even then, an unmanned ship will always cause some doubt as to its ability to react as a human would react.

D. OBJECTIVES

During initial formulation of the problem statement, five objectives were identified that served to measure progress towards evaluating the USC concept.

1. The first objective was to define the problem and scope of the project. To achieve this objective, the missions and top level system requirements for the USC were determined and a USC Capabilities Matrix was developed.

2. The second objective was to perform an operational analysis. The analysis was based on an assessment of the current relevant technologies for a USC and an exploration of

considerations required to fully automate the USC. Lastly, a CORE model and Concept of Operations was developed for the USC.

3. The third objective was to analyze USC functions. The relevant technologies were examined and the USC functions were analyzed using three autonomous stressing scenarios.

4. The fourth objective was to evaluate the USC relevant technologies and identify potential design issues. The result was relevant technologies that addressed USC requirements.

5. The fifth and final objective was to evaluate the USC considerations and provide recommendations for further study. The evaluation was performed by comparing the USC concept to current manned ships.

E. SYSTEMS ENGINEERING PROCESS MODEL

The project team chose a modified waterfall systems engineering process model because of the streamlined approach of the model. The vast scope and relatively limited time for completion of this project precluded the project team from selecting an iterative process model. The five steps of the waterfall process as modified are: Need Analysis, Operational Analysis, Functional Analysis, Concept Discussion, and Final Analysis. A diagram of the process used is shown below in Figure 1.

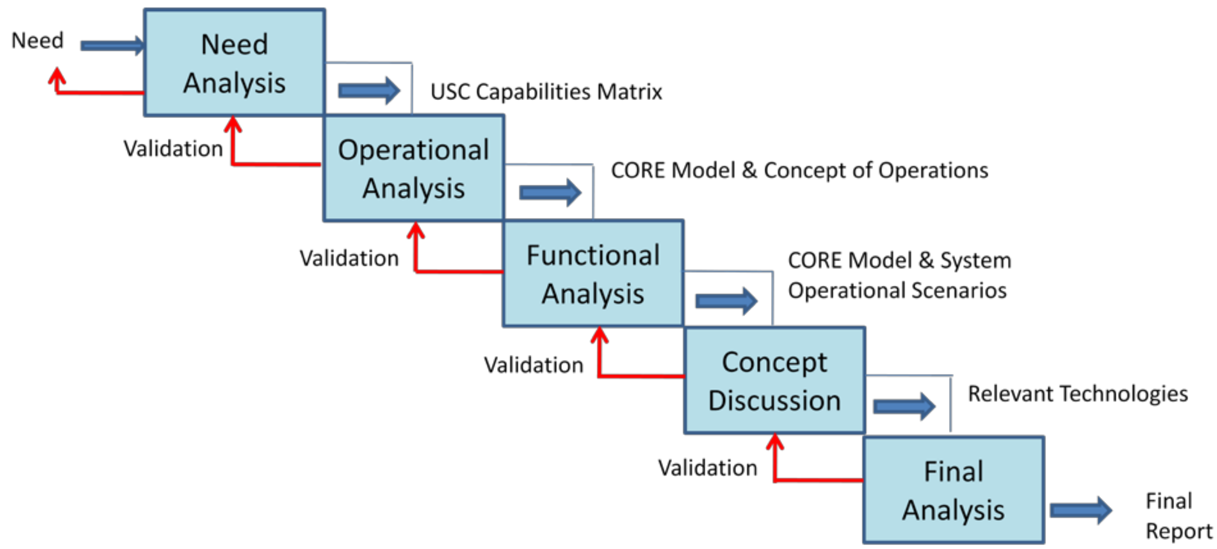

Figure 1. Modified Systems Engineering Process Model

The process began with the need. The need for this project was originally derived from the project assignment provided by the capstone advisors. This need was further articulated by the team (see Background) based on research and discussions with interested parties. Each process step had two resultant components - deliverables and validation. The deliverables drove the requirements for the subsequent step. All process step deliverables were assimilated and resulted in the last deliverable, this final report.

The validation process ensures that the deliverables produced met the requirements that began the process step. Validation was performed by comparing the deliverables at the end of process step with the beginning requirements of that step. If the new deliverables could be traced back to the requirements then the validation was successful. If changes were necessary because results were not validated, modifications to previous deliverables and the project management plan were made accordingly. The project team used CORE, a systems engineering and architecture software package, to track the USC concept operational and functional architecture throughout the systems engineering process.

All data, research, and technology information was collected from publicly available sources. No sensitive or classified material was used to develop the report. In some limited cases in the

report, the team had access to sensitive data of higher quality. For the most part, the project team was able to find comparable data publicly as well. The project team chose to use only publicly available information because it would allow for a wider distribution of the report and enable all readers to verify reference information.

F. SUMMARY

Section I of the report described the unmanned surface combatant need and the background for developing an autonomous USC. Cost savings, improved efficiency, and expanded capabilities are all reasons to investigate an autonomous USC. This section also included the report objectives for exploring the USC concept and the systems engineering process model used to achieve the objectives and complete the report. Validation and deliverables were part of each step in the systems engineering process model. The next section will define the USC concept problem and discuss the high level requirements and functions of the USC concept.

II. PROBLEM DEFINITION

This section of the report analyzes the need for an autonomous USC and identifies the military missions for the USC concept. Once the military missions are identified, those choices are confirmed by interested party survey results. The top level system constraints and lower level operational constraints are defined. A Concept of Operations for a notional USC is presented and functions are identified. The operational constraints are allocated to the functions, and several operational scenarios are presented to show actions which would stress the capabilities of an autonomous USC.

A. NEEDS ANALYSIS

1. Autonomous USV State of the Art

While there are currently no unmanned surface combatants, there are a number of unmanned surface vehicles (USV's) under development that are projected to accomplish a variety of

missions. USV's are envisioned as mission packages to be carried to the field by a manned platform such as LCS. Once in theater, they are sent out to accomplish short duration missions with controls and monitoring being accomplished from the manned platform. Although these USV's are useful to keep the manned platform out of harm's way, they do not contribute to reducing manning or eliminating the platform.

The largest class of USV as defined by the Navy Unmanned Surface Vehicle Master Plan [PEO LMW, 2007] is the Fleet Class (11m). The requirements for this class include providing adequate power, speed and payload for ASW, power and tow force for MCM Sweep, and endurance for these and other missions. This class of USV is to be deployed by LCS. Some of the USV designs are mature, but the USV's are limited in scope (limited missions, one mission at a time), and are mostly line-of-sight, remotely monitored and controlled. Hull, sensors and limited weapons are mature technologies for USV's.

The Defense Advanced Research Projects Agency (DARPA) is also funding the ASW Continuous Trail Unmanned Vessel (ACTUV) program which has the goal of sending an unmanned vessel for long term submarine tracking on its own (concept design has a 30 day loiter followed by 30 day maximum energy trail mission). This project is in its preliminary stages, currently completing phase 1. This phase explores development and at-sea demonstration of USV autonomous algorithms for submarine tracking, and "rules of the road" compliance [Jane's Unmanned Maritime Vehicles and Systems1, 2011]

Appendix A summarizes the state of current USV technology, including the Fleet Class USV previously mentioned. Most USV's are in the 4-11m range in length, can operate in Sea State 3, survivable to Sea State 5, with a payload capacity of around 2500kg and endurance of less than 48 hrs. The Piranha is an exception to the above, it is a Fleet Class with composite hull, 54 ft in length with a 15,000 lb max payload, an endurance of 40 days and survivable to Sea State 6 [Jane's Navy International1, 2011]. Generally, the size of the USV limits its payload and the missions it can accomplish, as well as the amount of fuel it can carry and associated range and endurance, and survivability in high sea states. The X-3 is partially solar powered and can be deployed for 60 days, but is not currently suitable for other than ISR functions [LaGrone, 2011].

<u>Leveraging USV Designs for USC needs</u>

The goal of a USV is usually single mission, close to shore or other manned platform, whereas the goal of a USC is to take the place of a surface combatant such as LCS, and replace the platform itself.

As the requirements indicate, the main concerns of the USV design tradeoffs are adequate power and speed, payload, tow force for ASW and MCM Sweep, endurance, as well as fit and transportability, which are all constraints of its small size. Extrapolating from the Piranha performance indicates that these constraints are reduced with a larger platform. USV technologies that can be leveraged for the USC program include navigation, collision/obstacle avoidance, and onboard C4I, such as resident on the Silver Marlin, which is based on UAV technology [Jane's Unmanned Maritime Vehicles and Systems2, 2011]. Autonomous navigation is a complex field which is being extensively researched by SIS, Inc. and JPL for the AMN and ACTUV project and is described in the article "The Autonomous Maritime Navigation (AMN) Project: Field Tests, Autonomous and Cooperative Behaviors, Data Fusion, Sensors, and Vehicles" in the Journal of Field Robotics, August 2010. However, adapting this technology will have to take into consideration the larger size of the USC.

Other USV developments that can be used on a USC include winch deployment of tow fish which can be deployed remotely by many USV's; the FAST has an unmanned influence sweep system in the capability concept demonstrator phase [Jane's Unmanned Maritime Vehicles and Systems3, 2011]; the Inspector Mk2 has a patented dedicated keel to carry acoustic sensors such as multi-beam echo sounder, swath bathymetric sonar, sub-bottom profiler or acoustic Doppler current profiler [Jane's Unmanned Maritime Vehicles and Systems4, 2011]; the Venus-9 USV has a Weapon of Mass Destruction Detector System which successfully demonstrated its capabilities to detect radioactive materials and targets [Jane's Unmanned Maritime Vehicles and Systems5, 2011]. ACTUV is also exploring a C2 system to enable global operations of remotely supervised systems, de-fouling and other self-maintenance capabilities, and unique payload systems that could benefit from the extended periods of uninterrupted operations [Jane's Navy International2, 2010]. These technologies can be adapted to the USC. Software and

autonomous controls are currently not mature technologies in the U.S.

Some of the risk areas for the USC which cannot leverage development of USV's include navigation in crowded shipping lanes with a large hull, docking, refueling at sea, self defense and possibly autonomous use of lethal weapons. Some USV's are equipped with small guns but they are remotely controlled. Because of its longer range and endurance, non line of sight communications and data transfer are a major factor for the USC which is generally not the case for USV's.

2. General Autonomous Unmanned Benefits

The USC concept was worth exploring because it offers three distinct potential advantages over a manned combatant: cost savings, improved performance on some current capabilities and missions, and expanded capabilities and missions, with no risk to the crew. A successful autonomous unmanned surface combatant design would perform current missions more effectively, more efficiently, and less costly than a manned combatant. Also, there are some areas where a USC could perform beyond the limits of a manned alternative.

a) Cost Savings

Potential savings for eliminating manning is high. Manning accounts for approximately 15 percent to 39 percent of a ship's total life cycle cost. Current ship manpower costs give a rough idea of what potential savings could be realized [Elmendorf, 2010]:

Table 1 shows that fielding an (equivalently capable) unmanned ship can affect an average savings in manpower of about $18 million per year per ship. This value does not include other costs for human systems and support indirectly incurred to sustain and provide for manning. . At 286 ships currently in the fleet [US Navy3, 2011], the savings would be substantial even if only a small portion of ships can be replaced with unmanned surface combatants.

Table 1. Surface Ship Life Cycle Costs

Ship Class	MCM 1	FFG 7	DDG 51	CG 47	LCS 1
Total Life Cycle Cost per Ship	$631M	$1500M	$3042M	$4031M	$1063M
Personnel % Cost of Life Cycle	39%	34%	29%	29%	15%
Total Personnel Cost for Life Cycle	$243M	$510M	$897M	$1156M	$161M
Personnel Cost per Year for Life Cycle	$8M	$17M	$26M	$33M	$6M

b) Improved Performance for Current Capabilities and Missions

Use of machines to do certain US Navy ship tasks should be exploited where those tasks are more suitable for machines than humans. These tasks are generally monotonous and/or difficult for sailors to perform vigilantly. Numerous USN tasks fit this description such as round-the-clock surveillance and submarine hunting. These tasks are monotonous and difficult for sailors to focus on and can theoretically be accomplished more efficiently by machines and can be automated. By automating these machine suitable tasks, the manned combatants are deployed fewer times, and only to pursue other important missions where a human presence is necessary.

c) Expanded Capabilities and Missions

An unmanned surface combatant would allow the Navy to operate in dangerous waters without endangering sailors' lives. The USC can be sent into harm's way to carry out surveillance and reconnaissance missions in hostile water, perform MIW, and verify Chemical, Biological, Radiological (CBR) environments, without having to consider crew safety. Incidents such as the USS Cole and numerous other attacks on US ships could be less costly if the same missions could be carried out by an unmanned surface combatant.

3. US Naval Mission Areas and Autonomous Unmanned Operations

Navy surface combatant missions are described in OPNAVINST C3501.2H, (Naval) Warfare Mission Areas and Required Operational Capability/Projected Operational Environment Statements. The OPNAVINST divides each mission area into operational capabilities, which are further divided into sub-operational capabilities. Each capability and mission area was examined from the

prospective of being accomplished by an unmanned surface combatant and assigned a rating of red, yellow or green. The color indicates the team's judgment of the possibility a capability can be performed autonomously. A much more rigorous evaluation would be required for selecting USC attributes. Red indicates the mission cannot be done or is not beneficial to be done autonomously; yellow indicates it can be done but may be limited, too complicated or of marginal benefit to be done autonomously; and green indicates it can be done and it is beneficial to do so autonomously. OPNAVINST C3501.2H's eleven Naval Warfare Mission areas are defined below while sub-operational capabilities are highlighted with a brief discussion of each Mission area to show the overall USC applicability.

Anti-air Warfare (AAW) is the destruction or neutralization of enemy air platforms and airborne weapons, whether launched from air, surface, subsurface, or land platforms. The sub-operational capabilities shown below range from ship self defense which is rated green and considered a requirement, to overall control of combat air patrols, which is rated red and considered too much to automate. The former is much more conducive to performance by an unmanned combatant than the latter. An assessment was conducted and it was determined that most of the capabilities were beneficial to automate. Of the ten sub-operational capabilities, six were rated green, three yellow and one red. Overall, this mission area was rated green and it was determined that most of the capabilities were beneficial to automate but his was not selected as a priority mission.

Table 1. Anti-air Warfare sub-operational capabilities

AAW 1 (U) Provide anti-air defence in cooperation with other forces.	G		
AAW 2 (U) Provide anti-air defense of a geographic area (zone) in cooperation with other forces.	G		
AAW 3 (U) Engage air targets during BG operations in cooperation with other forces.	G		
AAW 4 (U) Provide for air operations in support of airborne anti-air operations.		Y	
AAW 5 (U) Conduct airborne anti-air operations.		Y	
AAW 6 (U) Detect, identify, and track air targets.	G		
AAW 7 (U) Control Combat Air Patrol (requires full allowance of Air Intercept Controllers (AICs).			R
AAW 8 (U) Engage air targets using installed air-to-air weapons systems.	G		
AAW 9 (U) Engage airborne threats using surface-to-air armament.	G		
AAW 10 (U) Coordinate the overall conduct of AAW operations with all other warfare requirements of the Amphibious Task Force (ATF) Commander. Allocate air assets as required to counter threats to the ATF.		Y	

Amphibious Warfare (AMW) involves attacks, launched from the sea by naval forces and by landing forces embarked in ships or craft, designed to achieve a landing on a hostile shore. This

includes fire support of troops in contact with enemy forces through the use of close air support or shore bombardment. The sub-operational capabilities shown below range from troop and equipment transport to evacuation of casualties. Of the eighteen sub-operational capabilities, four were rated green, one yellow and thirteen red. Overall this mission area was rated yellow and it was determined that most of the capabilities were not beneficial to automate. This mission area was people and cargo intensive and not well suited to an unmanned combatant.

Table 2. Amphibious Warfare sub-operational capabilities

AMW 1 (U) Load, transport and land combat equipment, material and supplies with attendant personnel in an amphibious assault.			R
AMW 2 (U) Load, transport, and land elements of a landing force with their equipment and supplies in an amphibious assault.			R
AMW 3 (U) Reembark and transport equipment, materials, supplies, and personnel.			R
AMW 4 (U) Serve as primary control ship in ship-to-shore movement.			R
AMW 5 (U) Conduct landing craft or amphibious vehicle operations in support of amphibious assault.			R
AMW 6 (U) Conduct helicopter operations in support of amphibious assault.			R
AMW 7 (U) Provide amphibious assault construction support for ship-to-shore operations and beach clearance.			R
AMW 8 (U) Provide for surface/subsurface defenses of an AOA.			R
AMW 9 (U) Conduct pre-assault cover and diversionary actions.	G		
AMW 10 (U) Conduct beach party operations in support of an amphibious assault.			R
AMW 11 (U) Conduct amphibious cargo handling operations.			R
AMW 12 (U) Provide air control and coordination of air operations in an AOA.		Y	
AMW 13 (U) Provide the naval element of the shore party to facilitate the landing and movement over the beaches of troops, equipment, and supplies, and to assist the evacuation of casualties/Prisoners of WAR (POW).			R
AMW 14 (U) Support/conduct Naval Gunfire Support (NGFS) against designated targets in support of an amphibious operation.	G		
AMW 15 (U) Provide for air operations in support of amphibious operations.			R
AMW 16 (U) Conduct close air support in support of an amphibious operation using air launched armament.	G		
AMW 17 (U) Conduct Vertical Short Take-Off and landing (VSTOL) flight operations in support of amphibious assault.			R
AMW 18 (U) Conduct Inshore Undersea Warfare (IUW) operations.	G		

Anti-surface Ship Warfare (ASU) is the destruction or neutralization of enemy surface combatants and merchant ships. Of the thirteen sub-operational capabilities shown below, nine were rated green, two yellow and two red. Overall this mission area was rated green and it was determined that most of the capabilities were beneficial to automate.

Table 3. Anti-surface Ship Warfare sub-operational capabilities

ASU 1 (U) Engage surface threats with anti-surface armaments.	G		
ASU 2 (U) Engage surface targets during BG operations in cooperation with other forces.	G		
ASU 3 (U) Support anti-surface ship defense of geographical area (e.g. zone or barrier) in cooperation with other forces.	G		
ASU 4 (U) Detect, identify, localize, and track surface ship targets.	G		
ASU 5 (U) Conduct Acoustic Warfare (AW) against surface contacts.	G		
ASU 6 (U) Disengage, evade, and avoid surface attack.	G		
ASU 7 (U) Conduct coordinated air attack (including the functions of Tactical Air Coordinator Airborne (TAC (A)) on targets.		Y	
ASU 8 (U) Provide for air operations in support of antisurface attack operations.			R
ASU 9 (U) Conduct attacks on surface ships using air launched armament.	G		
ASU 10 (U) Conduct airborne operations in support of anti-surface attack operations.		Y	
ASU 11 (U) Perform duties of Aircraft Control Unit (ACU) for aircraft involved in ASU operations.			R
ASU 12 (U) Support/conduct independent ASU operations.	G		
ASU 13 (U) Conduct pre-attack deception operations.	G		

Anti-submarine Warfare (ASW) is the destruction or neutralization of enemy submarines. Of the eight sub-operational capabilities shown below, six were rated green, one yellow and one red. Overall this mission area was rated green and it was determined that most of the capabilities were beneficial to automate. This mission area is well suited to an automated mission since it is tedious and time consuming and an autonomous system is not going to become tired or bored and this was selected as the first of two primary missions for the USC.

Table 4. Anti-submarine Warfare sub-operational capabilities

ASW 1 (U) Provide ASW defense against submarines for surface forces, groups and units.	G		
ASW 2 (U) Provide ASW defense of a geographic area.	G		
ASW 3 (U) Conduct independent ASW operations.	G		
ASW 4 (U) Conduct airborne anti-submarine operations.		Y	
ASW 5 (U) Provide for air operations in support of airborne anti-submarine operations.			R
ASW 6 (U) Engage submarines in cooperation with other forces.	G		
ASW 7 (U) Engage submarines with anti-submarine armament.	G		
ASW 8 (U) Disengage, evade, avoid, and deceive submarines.	G		

Command, Control and Communications (CCC) is providing communications and related facilities for coordination and control of external organizations or forces and control of unit's own facilities. Of the sixteen sub-operational capabilities shown below, nine were rated green, four yellow and three red. Overall this mission area was rated green and it was determined that most of the capabilities were beneficial to automate. This capability was considered a basic requirement for any surface combatant and crucial to the success of an USC.

Table 5. Command, Control and Communications sub-operational capabilities

CCC 1 (U) Provide command and control facilities for a task organization commander and staff.			R
CCC 2 (U) Coordinate and control the operation of the task organization or function force to carry out assigned missions.			R
CCC 3 (U) Provide own unit's command and control functions.	G		
CCC 4 (U) Maintain Navy Tactical Data System (NTDS) or data link capability.	G		
CCC 5 (U) Provide airborne capability to relay command and control communications to strategic forces.		Y	
CCC 6 (U) Provide communications for own unit.	G		
CCC 7 (U) Implement Operations Security (OPSEC) measures and conduct military deception actions.	G		
CCC 8 (U) Provide a reliable and survivable communications relay capability to deploy strategic forces.			R
CCC 9 (U) Relay naval communications.	G		
CCC 10 (U) Provide special communications.	G		
CCC 11 (U) Provide capability to conduct one or more of the five control functions: MPACU, Air Raid Reporting Control Ship, Aircraft Control Unit (ACU) for varios Anti warfare capabilities, PIRAZ/Strike Support Ship, and NTDS Link 11 Net Control Ship/Station (NCS).	G		
CCC 12 (U) Maintain capability to super encrypt cryptographically covered communications circuits.	G		
CCC 13 (U) Provide communications support for tactical surface, submarine, and air units.	G		
CCC 14 (U) Provide DCS connectivity/circuitry.		Y	
CCC 15 (U) Maintain and operate a Fleet Telecommunications Operation Center (FTOC).		Y	
CCC 16 (U) Function as the Navy Satellite Communication Network Area Control Activity.		Y	

Electronic Warfare (ELW) is the effective use by friendly forces of the electromagnetic spectrum for detection and targeting while deterring, exploiting, reducing, or denying its use by the enemy. Of the seven sub-operational capabilities shown below, six were rated green, one yellow and none red. Overall this mission area was rated green and it was determined that most of the capabilities were beneficial to automate but that the determination of how to handle EW was best left to individuals to assess the diplomatic and BG or SAG impacts and not well suited to a USC.

Table 6. Electronic Warfare sub-operational capabilities

ELW 1 (U) Conduct Electronic Warfare Support Measures operations.	G		
ELW 2 (U) Conduct Electronic Countermeasures operations.	G		
ELW 3 (U) Conduct Electronic Counter-Countermeasure operations.	G		
ELW 4 (U) Conduct Electromagnetic/Acoustic Emission Control operations.	G		
ELW 5 (U) Conduct coordinates electronic warfare operations with other forces in support of a BG or SAG.	G		
ELW 6 (U) Conduct counter-targeting through electronic and/or acoustic means.	G		
ELW 7 (U) Plan/conduct Command, Control, and Communication Countermeasure (C3CM) operations via physical, technical, and administrative means.		Y	

The Intelligence (INT) capability is the collection, processing, and evaluation of information to determine location, identification and capability of hostile forces through the employment of reconnaissance, surveillance, and other means. With the exception of the Navy intelligence vessels (i.e. T-AGM Class), all Navy surface combatants are required to have limited amounts of this capability to carry out its mission. Of the eight sub-operational capabilities shown below, all were rated green, no yellow or red. Overall this mission area was rated green and it was determined that most of the capabilities were beneficial to automate. However, since there are only two Navy intelligence vessels currently deployed, this did not appear to be a good primary function for an unmanned vessel due to the high technology cost for a small ship class. Additionally, an unmanned intelligence ship would push the envelope on the overall TRL level of the ship design due to the amount of man-in-the-loop decisions that would need to be replaced.

Table 7. Intelligence sub-operational capabilities

INT 1 (U) Support/conduct intelligence collection.	G		
INT 2 (U) Provide intelligence.	G		
INT 3 (U) Conduct surveillance and reconnaissance.	G		
INT 4 (U) Provide the capability to conduct ocean surveillance operations against targets of interest.	G		
INT 5 (U) Provide the capability to process ocean surveillance information.	G		
INT 6 (U) Conduct surface reconnaissance.	G		
INT 7 (U) Support/conduct airborne reconnaissance.	G		
INT 8 (U) Process surveillance and reconnaissance information.	G		

The Mine Warfare (MIW) capability is the use of mines for control/denial of sea or harbor areas, and mine countermeasures to destroy or neutralize enemy mines. Of the eleven sub-operational

capabilities shown below, seven were rated green, one yellow and three red and this overall mission area was rated green. This mission area, like ASW, is well suited to an automated mission since it is tedious and time consuming. It was determined that most of the capabilities were beneficial to automate and this was selected as the second of two primary missions for the USC.

Table 8. Mine Warfare sub-operational capabilities

MIW 1(U) Conduct moored mine countermeasures.	G		
MIW 2 (U) Conduct influence mine countermeasures.	G		
MIW 3 (U) Conduct mine neutralization/destruction.	G		
MIW 4 (U) Conduct mine countermeasures (MCM).	G		
MIW 5 (U) Support/conduct offensive/defensive mine-laying operations.		Y	
MIW 6 (U) Conduct magnetic silencing (degaussing, deperming, etc.).	G		
MIW 7 (U) Assemble, test, maintain, and issue mines.			R
MIW 8 (U) Conduct precise navigation.	G		
MIW 9 (U) Conduct airborne mine countermeasures.			R
MIW 10 (U) Provide for air operations in support of mine warfare operations.			R
MIW 11 (U) Conduct Route Survey Operations.	G		

The Mobility (MOB) capability is the ability of naval forces to move and to maintain themselves in all situations over, under, or upon the surface. All vessels are required to have this capability regardless of mission selection. Of the fifteen sub-operational capabilities shown below, four were rated green, no yellow and eleven red and this overall mission area was rated red. Mobility would ultimately be identified in the design as a derived requirement.

Table 9. Mobility sub-operational capabilities

MOB 1 (U) Steam to designed capability and in the most fuel efficient manner.	G		
MOB 2 (U) Support/provide safe, flyable aircraft for all-weather operations.			R
MOB 3 (U) Prevent and control damage.	G		
MOB 4 (U) Transfly on short notice.			R
MOB 5 (U) Maneuver in formation.	G		
MOB 6 (U) Refuel in the air.			R
MOB 7 (U) Perform seamanship, airmanship, and navigation tasks.	G		
MOB 8 (U) Operate from a ship.			R
MOB 9 (U) Maintain nuclear propulsion readiness.			R
MOB 10 (U) Replenish at sea.		Y	
MOB 11 (U) Maintain mount-out capabilities.			R
MOB 12 (U) Maintain the health and well-being of the crew.			R
MOB 13 (U) Maintain reserve unit mobilization readiness (inactive reserve units only).			R
MOB 14 (U) Conduct operations ashore.			R
MOB 15 (U) Conduct parachute operations.			R

The Naval Special Warfare (NSW) capability requires naval operations generally accepted as being unconventional--in many cases clandestine--in nature. NSW includes special mobile operations, unconventional warfare, coastal and river interdiction, beach and coastal reconnaissance and certain tactical intelligence operations. The sub-operational capabilities were considered for evaluation but due to the mandatory personnel involved and this mission area was rated red. Of the eight sub-operational capabilities shown below, four were rated green, no yellow and four red and this mission area was rated red.

Table 10. Naval Special Warfare sub-operational capabilities

NSW 1 (U) Conduct hydrographic reconnaissance.	G		
NSW 2 (U) Clear the seaward approaches to amphibious landing beaches.	G		
NSW 3 (U) Conduct maritime sabotage.	G		
NSW 4 (U) Conduct combatant craft operations.			R
NSW 5 (U) Conduct Unconventional Warfare operations.	G		
NSW 6 (U) Conduct counterinsurgency operations.			R
NSW 7 (U) Support raiding parties.			R
NSW 8 (U) Conduct limited local security defensive combat operations.			R

The Strike Warfare (STW) capability requires the destruction or neutralization of enemy targets ashore through the use of conventional or nuclear weapons. This includes, but is not limited to,

strategic targets, building yards, and operating bases from which the enemy is capable of conducting air, surface, or subsurface operations against U.S. or allied forces. This mission area was given some consideration. Of the ten sub-operational capabilities shown below, seven were rated green, three yellow and no red. Despite this, it was deemed too risky to have an unmanned vessel firing ashore and this mission area was rated red.

Table 11. Strike Warfare sub-operational capabilities

STW 1 (U) Maintain readiness to deliver ballistic missiles on assigned targets.	G		
STW 2 (U) Conduct operational tests of ballistic missile weapons system.	G		
STW 3 (U) Support/conduct multiple cruise missile strikes either independently or in support of other strike forces.	G		
STW 4 (U) Support/conduct air strikes.	G		
STW 5 (U) Conduct coordinated air strikes/attacks (including the functions of TAC (A)) on targets.	G		
STW 6 (U) Support/conduct airborne operations in support of other strike forces.	G		
STW 7 (U) Conduct airborne operations in support of air strike operations.	G		
STW 8 (U) Provide for air operations in support of air strike operations.		Y	
STW 9 (U) Conduct attacks on targets using air launched armament.		Y	
STW 10 (U) Perform duties of ACU for Strike Warfare Operations.		Y	

Based on the above evaluation the team selected ASW and MIW as the two primary military missions and CCC as the primary support mission to pursue. Three operational areas were eliminated MOB, NSW and STW. The remaining five areas were determined to be less than optimal for the USV but some of the sub-operational capabilities would be required for a USC to conduct self defense, intelligence, surveillance, and reconnaissance (ISR) and electronic warfare tasking.

4. Military Missions Selection for USC Constraints Discussion

The team chose ASW and MIW as the two military missions to pursue based on the high potential to leverage the benefits of autonomous unmanned operations for these missions. This decision was also supported by the interested party survey results. Both ASW and MIW missions generally involve an extensive search of large areas looking for small signature targets. This is tedious, and tests the patience of human operators. USC's can be programmed to perform detailed searches that would otherwise be frustrating to the human operator.

Mine Warfare

MIW is a mission ideally suited for unmanned operations. A USC using onboard and offboard sensors (e.g. UUVs or sonobouys) and working with other USCs or manned ships can synthesize sonar data and tirelessly mine it for information. Using GPS and computerized pattern searching, the USC could optimize the area to be searched and cleared. Mine clearance is a dangerous but necessary task for the US Navy. "Since the end of World War II, mines have seriously damaged or sunk four times more US Navy ships than all other means combined…The principal objective of the Navy's Mine Countermeasures Vision is to decrease significantly the time required to conduct countermeasures operations, while ensuring low risk to naval and commercial vessels, and to remove the man from the minefield [PEO-LMW1,2009]." The design and deployment of an unmanned mine countermeasures ship fits well with these plans. The USC can be sent into harm's way to carry out mine countermeasure missions without fear of human casualties and, with the right planning, without constant remote operation or manned support.

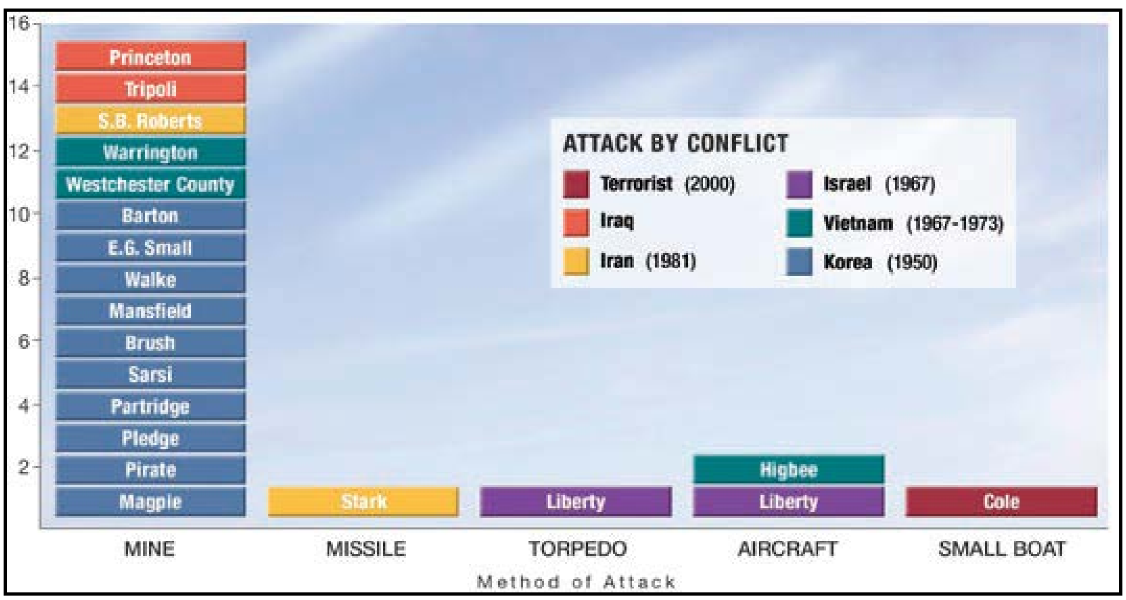

Figure 2. **Mines have damaged or sunk four times more U.S. Navy ships than all other means of attack [PEO-LMW1,2009].**

The casualties listed above include human lives as well as ships. Figure 2 clearly indicates the need to pursue the safer unmanned alternatives to accomplish the unenviable and dangerous task of clearing underwater mines.

Anti-Submarine Warfare

A single submarine poses a threat that can have an adverse effect on our sea-based operations and US Navy sea control and power projection strategies. "We must recognize that in today's and tomorrow's conflict scenarios, the submarine is an underwater terrorist, an ephemeral threat. It will force us to devote a great deal of resources and time, which we might not have…The near-shore regional/littoral operating environment poses a very challenging ASW problem. We will need enhanced capabilities to root modern diesel, air-independent, and nuclear submarines out of the "mud" of noisy, contact-dense environments typical of the littoral..." [Morgan, 1998].

ASW is another military mission where autonomous unmanned attributes will enhance the ability of the ship to perform the mission. In the US Navy's current environment, the number of SSN's is expected to decrease. Use of an unmanned ship with automated sensors to gather data and perform 24 hour surveillance is a viable approach for the task of essentially looking for needles in a haystack. Conducting detailed searches can be monotonous and unrewarding for human operators and human vigilance will decrease as task time increases. Additionally, the USC performing ASW will free up the SSN's for more important missions. Several USC's working together could use organic or air dropped sonobouys and dipping sonar to create a multi-static sonar network to acquire and prosecute a contact. The US Navy is already shifting to more unmanned systems: "…the networking of self-aware, autonomous sensor fields coupled with manned and unmanned kill vehicles will shift ASW from "platform-intensive" to "sensor-rich" operations. Sensors and networks will enable effective employment of weapons and platforms to a greater degree than ever before." [ASW Taskforce, 2011]

5. Interested Party Survey Results

The project team identified interested parties based on who the team felt would influence design decisions for the US Navy, had expertise in the required technical areas, and would be reviewing the Capstone project when complete. Some of these interested parties completed a survey ranking the importance of USC missions, while others provided significant guidance and resources throughout the research portion of the project. Interested parties are listed below:

- Dr. Jeffrey Beach – NPS - Project Advisor
- Professor Mike Green – NPS - Project Advisor
- Dr. Bob Brizzolara – Office of Naval Research
- Mr. Scott Littlefield – NSWC Carderock Division
- Mr. Bill Glenney – Strategic Studies Group
- Professor Chuck Calvano – NPS
- Professor Fotis Papoulias – NPS
- Dr. Jack Price – DDR&E/NSWC Carderock Division
- Mr. Jeff Koleser – NAVSEA 05D
- Mr. Matt Garner – NAVSEA 05D
- Mr. Brian Wolfe – NAVSEA 05D
- Mr. Tim Jones – NSWC Port Hueneme Division

Interested parties were each given a survey explaining the project and were asked for a relative comparison of the 11 possible combatant missions as they applied to a USC. The purpose of this survey was to determine whether the team mission choices of ASW and MIW were also accepted by a wider community as appropriate for a USC. A score of "5" indicated that the person considered that mission extremely important as compared to the other mission, where as a score of "1" indicated that both missions were of equal importance. A comment area helped explain the context for the person's choice. Below is an example question from the survey. The full survey is given in Appendix B.

Which Mission do you consider to be more important for the USC to support?

Anti-Air Warfare   Strike Warfare

5 4 3 2 1 2 3 4 5

Brief explanation or comments:

____

____

____

____

Once the surveys were completed, scores were entered into a pairwise comparison matrix and results tabulated. Results are listed below in Figure 3:

Missions	Weights
Anti-Air Warfare	0.0888
Amphibious Warfare	0.0262
Anti-surface ship warfare	0.0979
Anti-submarine Warfare	0.1330
Command, control and communications	0.1411
Electronic Warfare	0.0922
Intelligence	0.0644
Mine Warfare	0.1343
Mobility	0.0926
Naval Special Warfare	0.0562
Strike Warfare	0.0733

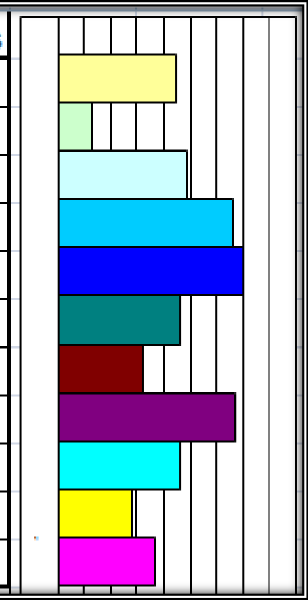

Figure 3. Survey Results

The top three ranked mission areas were Command, Control and Communications (C3); MIW; and ASW. Two of the top three choices confirmed the team's assessment that MIW and ASW were appropriate missions for a USC. In addition, C3 was determined to be important for a USC to perform regardless of chosen mission area, since knowing what the USC is doing and communicating orders and intent are critical to USC acceptance and success. Some sub-operational capabilities from Mobility were adopted in order to ensure precise navigation, and some sub-operational capabilities from Anti-Air Warfare and Anti-Surface Ship Warfare were adopted in order to ensure appropriate self defense measures.

B. TOP LEVEL SYSTEM CONSTRAINTS AND ASSUMPTIONS

Below is a list of top level constraints for the USC. The list includes Operational Constraints and System Wide Constraints.

1. Top Level Operational Constraints
   1.1. The USC should perform Anti-Submarine Warfare. This constraint was chosen by soliciting stakeholder input and performing a needs analysis and confirming with stakeholder input. ASW was determined to be a primary military mission for the USC Concept.

   1.2. The USC should perform Mine Warfare. This constraint was chosen by soliciting stakeholder input and performing a needs analysis and confirming it with stakeholder input. MIW was determined to be a primary military mission for the USC Concept.

2. Top Level System Wide Constraints
   2.1. Speed - The USC should be able to travel out ahead of a Carrier Strike Group (CSG) or Expeditionary Strike Group (ESG) to reach an assigned mission area. While the ASW and MIW mission speeds are not a driving constraint, the speed of the Strike Group should be considered as a primary factor in the choice of maximum speed. It is estimated the USC should have a maximum transit speed of 30 knots at maximum displacement to be able to transit to a mission area.

   2.2. Range - The range of the USC should be sufficient for it to deploy to the theater of operation (e.g., traverse the Atlantic Ocean) without refueling, plus have additional fuel to reroute in case of emergency. This range is estimated to be at least 4500 nautical miles and is similar to other surface combatants.

   2.3. Operational Availability - Reliability for an unmanned autonomous ship is extremely important because there will be no on board maintenance to fix any systems that fail. With no continuous onboard maintenance and the complex autonomous nature of the

USC, the Operational Availability (A_O) of the USC should be similar to the A_O of manned ships. It is estimated the USC should have a total system A_O of 0.95.

2.4. Survivability - The survivability level as defined in, OPNAVINST 9070.1 ‘SURVIVABILITY POLICY FOR SURFACE SHIPS OF THE U.S.”, was chosen for the USC because it is the lowest level required for a combatant ship to sustain operations in the immediate area of an engaged strike group. Because the USC will be a combatant and operate as part of strike group, Level II is estimated to be appropriate [OPNAV2, 1988].

2.5. Operational Sea State - Continuous operations through Sea State 5 (Beaufort scale) are a constraint for other surface combatants and it was chosen as the operational limit for the USC as well. While the ship is capable of operating at this sea state, there may be some mission capability degradation. The USC should operate through Sea State 5.

2.6. Survivable Sea State - The USC should survive through Sea State 8 (Beaufort scale) Surviving through Sea State 8 is a constraint for other surface combatants, and it was chosen as the survival limit for the USC as well.

2.7. Temperature Range - The USC will be used in similar environments as other surface combatants. MIL-STD-1399 Section 302 [US Navy, 1988] defines an operating temperature range of -29°C to +50°C for those combatants. Since the USC will be operating in similar environments it is estimated it will require a similar temperature range constraint of -29°C to +50°C.

2.8. Maintenance Cycle - Manned surface combatants currently in the fleet have availabilities scheduled approximately every 25 months in accordance with OPNAVNOTE 4700 [OPNAV3, 2010]. Because no Preventative Maintenance System (PMS) actions can be performed onboard the USC, the availability cycle needs to be shorter than that of manned ships. It is estimated that 12 months will allowed the USC to participate with a

strike group for a sufficient time period before needing to cycle out for maintenance. The USC should operate for 12 months between major maintenance availabilities.

2.9. Service Life - The USC should have a minimum service life of 25 years. This 25 year service life constraint is based on the LCS, which is a comparable surface ship [CBO, 2010].

2.10. Underway Replenishment - The USC should receive fuel resupply while underway so that it can maintain its pace with a strike group, or continue a persistent presence in a desired operational area.

2.11. Docking/Undocking - The USC should be able to dock and undock in the same manner and under the same conditions as other naval combatants.

3. Key Assumptions

a) The necessary rules of law, operating rules, and operating procedures are developed to allow for an unmanned, autonomous ship capable of firing weapons.

b) Technology for Fleet Class USV is mature enough to be applied to USC concept for target recognition, autonomous navigation, and weapons release [PEO- LMW2, 2007].

c) The USC should have an Initial Operating Capability (IOC) of 2020. The year 2020 was also chosen to limit the technologies that were considered for the USC concept. The intent is to leverages current technologies that may be able to be modified for fully autonomous operation.

d) The USC is a capital asset that should be capable of performing extremely dangerous missions. The technologies onboard will be state of the art, extremely capable, and valuable. The USC will be designed to withstand damage, control the damage and return to a safe operating area for assessment and repair. The ship is not considered

expendable at this time; however future detailed tradeoffs may result in an expendable concept.

e) The USC can operate as part of a battle group or strike force. The USC will have the alternate capability for remote control by a human for missions that are not possible or allowed to be done autonomously, such as use of lethal force against a manned craft. Human control can be assumed from a manned surface combatant or from remote station, with protocol for transfer of control in place.

f) The USC can operate alone without support for up to 60 days.

C. LOWER LEVEL OPERATIONAL CONSTRAINTS

The following list of operational constraints was derived from the top level constraints listed above. The list includes lower level constraints for the ASW and MIW missions as well as those for the USC ship system. The USC should be capable of supporting the following functions and sub-functions that are extracted from OPNAVINST 3501.2K [OPNAV1]:

1. Detect, localize, classify, identify, and track subsurface contacts
   1.1. Conduct area searches for subsurface contacts
   1.2. Provide capability to collect, store, retrieve, and process ASW contact data
2. Destroy or neutralize submarines with anti-submarine armaments
   2.1. Engage submarines
   2.2. Perform assessment of neutralization attempt
3. Disengage, evade, avoid, and deceive submarines
4. Detect, localize, and identify mines
   4.1. Conduct Route Survey Operations by SMCM ships/craft
   4.2. Provide collect, store, retrieve, & process MIW contact data capability
5. Destroy or neutralize mines
   5.1. Directly engage mines
   5.2. Perform area neutralization of mines
   5.3. Perform assessment of neutralization attempt
6. Navigate precisely in MCM environment
7. Provide own unit’s command and control functions

7.1. Process orders into executable actions

7.2. Recognizes situations based on preset conditions

7.3. Respond to situations by changing actions

8. Provide communication for own unit

8.1. Receive and interpret orders from command

8.2. Send reports to command

8.3. Communicate and interact logistics support vessel/facility

9. Receive and relay naval communications

10. Implement Operations Security (OPSEC) measures and conduct military deception actions

11. Maintain a precise global navigation system

12. Maneuver in formation

13. Perform anti-air self-defense

13.1. Detect, identify, and track air targets

13.1.1. Provide capability to collect, store, retrieve, and process air contact data

13.2. Destroy or neutralize airborne threats

13.2.1. Engage airborne threats

13.2.2. Perform assessment of neutralization attempt

13.3. Disengage, evade, and avoid air attack

14. Perform anti-surface self-defense

14.1. Detect, identify, and track surface targets

14.1.1. Provide capability to collect, store, retrieve, & process surface contact data

14.2. Engage surface threats

14.2.1. Engage airborne threats

14.2.2. Perform assessment of neutralization attempt

14.3. Disengage, evade, and avoid surface attack

15. Conduct electronic warfare

16. Assess self-health/damage

17. Control or minimize damage

18. Reconfigure systems to minimize performance reduction due to damage

19. Assess damage control measure success

20. Steam to designed capability and in the most fuel efficient manner

D. CONCEPT OF OPERATIONS

The *2010 Quadrennial Defense Review (QDR) Report* of February 2010 stated that there are growing threats from a number of states that have acquired sophisticated anti-ship cruise missiles, quiet submarines, and advanced mines that threaten naval operations. The Navy needs to exploit advantages in subsurface operations by developing unmanned underwater vehicles capable of a wide range of tasks. The capability to maintain Operating Areas clear of submarine-delivered and floating mines remains crucial.

The report also stated that confronting sophisticated anti-access challenges and threats posed by nuclear-armed regional adversaries presents a difficult problem. In addition, the globalization of the world’s chemical industry, coupled with scientific breakthroughs, increases the possibility of non-traditional chemical agents being used against the U.S. and allied forces.

Faced with these threats, it is highly desirable to develop a means of threat response that limits human exposure such as using unmanned assets. Furthermore, new approaches for projecting power must be developed to meet these threats while considering the current budget constrained environment and push towards minimization of personnel as one way of reducing costs. The scale and duration of operations overseas are placing a strain on service members and Department of Defense (DoD)’s ability to reset and reconstitute its All-Volunteer Force.

1. Users and Other Stakeholders

Program Executive Office (PEO) Ships would be the responsible acquisition agent for the USC, and would ensure that there is adequate testing, logistics support, and training for the successful operation, maintenance, replenishment, organic maintenance, and shore based or strike group based control and monitoring of the USC.

The USC would be part of the Atlantic (LANT) Fleet or Pacific (PAC) Fleet and commanded by the Expeditionary Strike Group or Carrier Strike Group in the theater of operations.

2. Policies

Policies:

The following policy documents apply:

- Quadrennial Defense Review Report, February 2010
- Naval Sea Systems Command (NAVSEA) Strategic Business Plan, 2009-2013

The USC would comply with all Federal Codes of Regulations, environmental, emissions, safety and navigational regulations in all US ports and abroad, including but not limited to:

- Article III of the Convention on the International Regulations for Preventing Collisions at Sea (COLREGS), 1972 (72 COLREGS)
- Marine Protection, Research, and Sanctuaries Act of 1972 (Public Law 92-532, October 23, 1972)
- Act to Prevent Pollution from Ships (APPS), January 2009 (MARPOL Annex VI)
- International Convention for the Safety of Life at Sea (SOLAS), 1974

3. Operations and Support Description

Operational Description

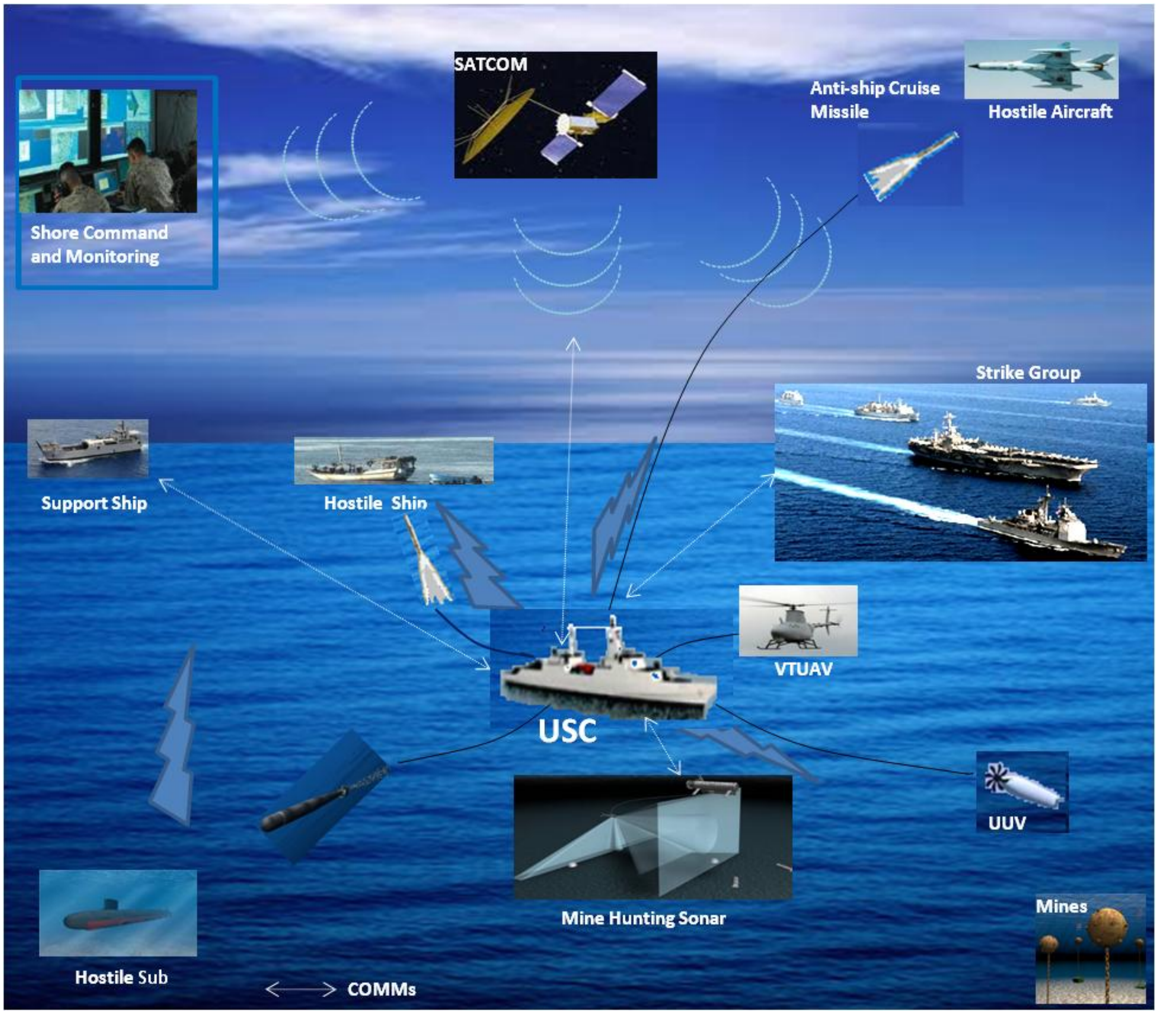

Figure 4. Unmanned Surface Combatant – OV-1

The Operational View-1, Figure 4 above, shows the USC in a notional operational area. The USC would have direct control and communication with potential unmanned auxiliary units that could be launched from the USC or other strike group members.

The USC would have tactical communication with the rest of the strike group and shore command through Satellite Communications (SATCOM). Shore command or a command ship

would take direct control of the USC only when necessary. Otherwise, shore command will only be monitoring the USC or giving orders for the USC to carry out.

The USC should expect to encounter both primitive and advanced threats. Primitive threats include mines and pirate artillery. Advanced threats include aircraft and attack submarines.

Missions

The USC initial concept would be a two mission autonomous combatant that will be deployed in similar situations as other surface combatants. It will be able to act as part of a strike group or individually. The USC would have complete situational awareness, be able to transfer data and information to and from other assets, and perform some command and control functions.

The first flight of the USC would complement the integrated Joint warfighting force by gaining initial entry, ensuring access and defeating enemy anti-access and / or area denial strategies in the areas of MIW and ASW. The majority of the missions is expected to be in littoral waters and are well suited for an autonomous USC concept due to the high risk of damage from mines, and persistence necessary for ASW missions.

The USC would perform mine hunting and mine sweeping functions. Using an unmanned ship removes the potential for loss of life during mine hunting and mine sweeping operations. In order to perform the mine warfare mission, the USC would have state-of-the-art sensors with data analysis and processing capabilities. The USC would have precise navigation and a high level of maneuverability. Lastly, the USC would engage potential mines with an effective mine neutralization system and assess the effect of those measures.

The USC would perform hold at risk, protected passage and maritime shield functions. By using an unmanned ship to perform ASW functions, a persistent naval presence can be maintained longer and possibly at a higher vigilance than a manned ship. In order to perform the anti submarine warfare mission, the USC would have state-of-the-art sensors and data analysis and processing capabilities. The USC would track, follow, engage, and evade a subsurface contact. If the contact is engaged, the USC would assess the success of the neutralization attempt.

Employment Modes

The following modes of operation would apply:

Transit: The USC would be able to navigate to the Operating Area (OPAREA) with or without escort, autonomously, with minimal oversight by shore base or manned ship based monitoring and control station.

Peacetime Mission: The USC would be involved in training missions in concert with Allied Forces. Navigation would be in autonomous mode with orders to be provided by the Theater Commander, and control of USC weapons potentially from other manned assets.

Wartime Mission: The USC would be able to perform ASW and MIW missions in hostile waters. The USC would carry out these missions autonomously, with remote settings/orders and some control by manned ship based control and monitoring by Theater Command and Control.

Maintenance: The USC's Self-defense would be able to be disabled remotely for boarding by maintenance personnel.

Scheduling and Operations Planning

The USC is envisioned to be available to support fleet missions on a continuous basis, with fueling and operational maintenance conducted by a support ship monthly when in theater, and availabilities every two years for hull maintenance in US or Allied port.

Operating Environment

The following is the projected operational environment as stated in Chief of Naval Operations Instruction (OPNAVINST) C3501.2K:

- At sea in war time.
- Capable of performing all offensive and defensive functions simultaneously while in Readiness Condition I (i.e., Defense Readiness Condition (DEFCON) 1, War is imminent).
- Capable of performing other functions which are not required to be accomplished simultaneously.
- Continuous Readiness Condition III (i.e., DEFCON 3, increase in force readiness above that required for normal readiness) at sea.

Geographic Areas

The USC should be able to operate on any navigable ocean/sea in the world, including the Margin Ice Zone (MIZ), up to 50% ice concentration, including but not limited to the Indian and Pacific Ocean coastal areas.

Environmental Conditions

The USC should be fully operable under all but the most extreme environmental conditions. At a minimum the USC should be operable in the same environmental conditions as other surface combatants.

Threats and Hazards

The USC is likely to encounter the following hazards:

- Difficult navigation (high traffic areas, rocky coasts)
- Hostile environment (hurricanes, high seas, corrosive salt)
- Marine mammals

The following threats are expected:

- Hostile forces with surface, air and underwater weapons
- Hostile intrusion and capture
- Hostile electronic warfare and ISR
- Hostile intelligence, surveillance and reconnaissance

Interoperability with Other Elements

The USC should be interoperable with other fleet assets and other USCs. Because the USC will be unmanned, interoperability is a major consideration in the concept formulation. Communication between the autonomous ship and remote control stations need to be comprehensive, and remote control and monitoring functions should be highly reliable. Interoperability needs to be considered for operations that are currently manned such as fueling at sea, docking, and parts ordering, and may impact more than the USC design.

Mission Support Description

Primary fuel replenishment would be provided by support ships during transit to and from areas of operation. The USC would also be capable of being refueled while in port for maintenance.

All routine or specific maintenance would be conducted by support ship or command ship personnel. Training would need to be provided, as well as support and repair parts, either onboard the support ship or onboard the USC. Onboard maintenance would be limited because the configuration would leverage the design trade space that an unmanned ship affords. The concept would minimize human access points to the ship components while underway.

The USC would monitor and diagnose its failed parts and provide a report to home base or the support ship, and would be able to order replacement parts or modules. Support ship, command ship and home base would have the ability to disable the USC's self-defense mechanisms and verify disarmament prior to boarding. The USC concept would strive toward redundant systems and modular parts which can be easily replaced at the organizational level. Some systems, such as damage control, machinery, C3, and navigation, should be designed with high reliability. At a minimum, the USC should be designed to stay afloat after a single hit, communicate with the home base, and navigate back to port if mobile.

The maintenance cycle would consist of 12 months of operational availability followed by maintenance availability. The length and scope of the availability would vary depending on the status of the USC. Additionally, low level interim maintenance would be performed on the USC while underway. All maintenance would be scheduled and coordinated by the USC's home base.

E. USC FUNCTIONS

Through a review of the needs analysis, system requirements, and CONOPS the project team identified the following functions for the USC concept. The functions include the military missions of ASW and MIW that were identified in the needs analysis as well as the general ship functions that must be performed to support the USC.

Military Mission Functions

1. Anti Submarine Warfare (ASW)

2. *Mine Warfare (MIW)*

General Ship Functions

3. Command, Control and Communication (C3)

4. Navigation

5. Self defense

6. Damage control

7. Machinery

Figure 5. C shows the functions displayed in the CORE Model. The CORE software is a model based system engineering tool used to organize and document requirements, functions, inputs and outputs while providing traceability of the information back to its source.

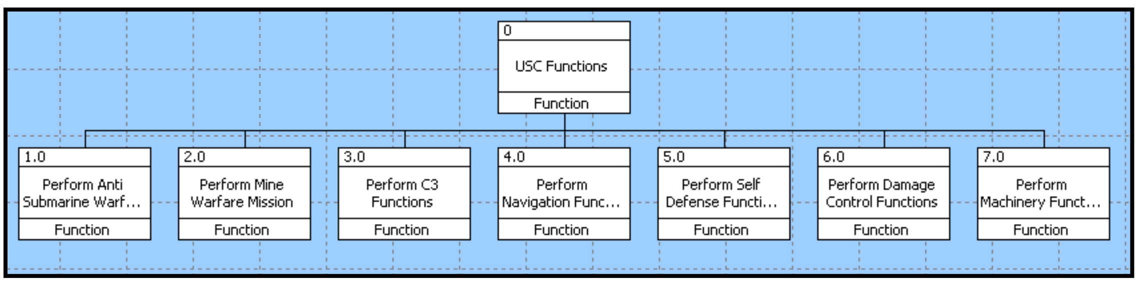

Figure 5. CORE Model High Level Functions for USC

These high level functions were further decomposed into twenty three lower level functions. An example of this functional decomposition for the two military mission functions is shown in Figure 6.

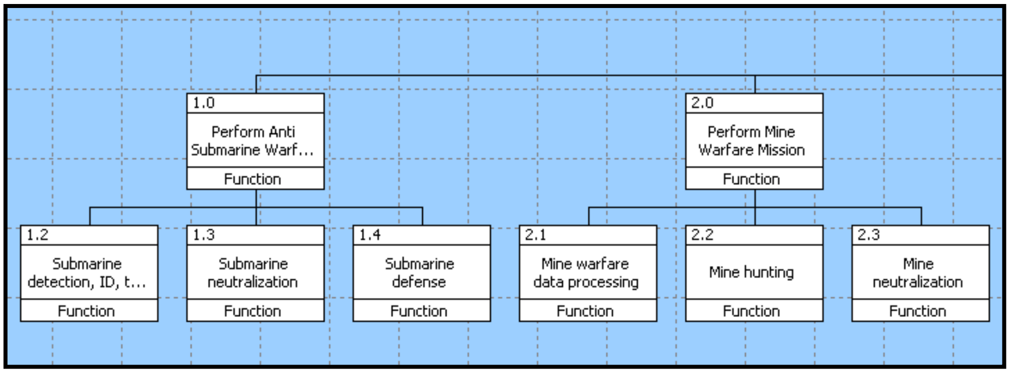

Figure 6. CORE Model Lower Level Functions for ASW and MIW

F. FUNCTIONAL ALLOCATION

After the seven high level functions of the USC were determined, the lower level operational requirements were allocated to each functional area. A review of the needs analysis, system requirements, CONOPS and OPNAVINST 3501.2K identified the functions for the USC concept and decomposed them to a lower level. The allocation is shown below and was tracked using the CORE model.

Functional Requirements

- 1.1. Perform ASW
  - 1.1.1. Detect, localize, classify, identify, and track subsurface contacts
    - 1.1.1.1. Conduct area searches for subsurface contacts
    - 1.1.1.2. Provide capability to collect, store, retrieve, and process ASW contact data
  - 1.1.2. Destroy or neutralize submarines with anti-submarine armaments
    - 1.1.2.1. Engage submarines
    - 1.1.2.2. Perform assessment of neutralization attempt
  - 1.1.3. Disengage, evade, avoid, and deceive submarines
- 1.2. Perform MIW
  - 1.2.1. Detect, localize, and identify mines
    - 1.2.1.1. Conduct Route Survey Operations by Surface Mine Countermeasures (SMCM) ships/craft
    - 1.2.1.2. Provide collect, store, retrieve, & process MIW contact data capability
  - 1.2.2. Destroy or neutralize mines
    - 1.2.2.1. Directly engage mines
    - 1.2.2.2. Perform area neutralization of mines
    - 1.2.2.3. Perform assessment of neutralization attempt
  - 1.2.3. Navigate precisely in a Mine Countermeasures (MCM) environment
- 1.3. Perform C3
  - 1.3.1. Provide own unit's command and control functions
    - 1.3.1.1. Process orders into executable actions
    - 1.3.1.2. Recognizes situations based on preset conditions
    - 1.3.1.3. Respond to situations by changing actions

1.3.2. Provide communication for own unit

1.3.2.1. Receive and interpret orders from command

1.3.2.2. Send reports to command

1.3.2.3. Communicate and interact logistics support ship/facility

1.3.3. Receive and relay naval communications

1.3.4. Implement OPSEC measures and conduct military deception actions

1.4. Perform navigation

1.4.1. Maintain a precise global navigation system

1.4.2. Maneuver in formation

1.5. Perform self defense

1.5.1. Perform anti-air defense

1.5.1.1. Detect, identify, and track air targets

1.5.1.1.1. Provide capability to collect, store, retrieve, and process air contact data

1.5.1.2. Destroy or neutralize airborne threats

1.5.1.2.1. Engage airborne threats

1.5.1.2.2. Perform assessment of neutralization attempt

1.5.1.3. Disengage, evade, and avoid air attack

1.5.2. Perform anti-surface defense

1.5.2.1. Detect, identify, and track surface targets

1.5.2.1.1. Provide capability to collect, store, retrieve, & process surface contact data

1.5.2.2. Engage surface threats

1.5.2.2.1. Engage airborne threats

1.5.2.2.2. Perform assessment of neutralization attempt

1.5.2.3. Disengage, evade, and avoid surface attack

1.5.3. Conduct electronic warfare

1.5.4. Perform pierside self defense

1.6. Prevent and control damage

1.6.1. Assess self health and damage

1.6.2. Control or minimize damage

1.6.3. Reconfigure systems to minimize performance reduction due to damage

1.6.4. Assess damage control measure success

1.7. Perform machinery functions

1.7.1. Steam to designed capability and in the most fuel efficient manner

G. SYSTEM OPERATIONAL SCENARIOS

The following operational scenarios were designed in order to determine which USC actions would stress the autonomous systems of the ship. Three scenarios were developed, one for each mission area, and one for non-normal operations such as self defense. Steps in the scenarios that were especially stressing to an unmanned ship (i.e., capabilities that are undeveloped for autonomous completion) are noted with **. These scenarios and stressing steps were used to guide the USC concept discussion.

1. Scenario 1 - Mine Scenario

A USC is navigating in formation with the Strike Group (SG). The USC sprints ahead to the littoral area and performs mine search and clearance. The USC detects and identifies mine like objects. The USC neutralizes the mine like objects. Once the area is clear the USC reports the results to the area command, and rejoins the SG. Once the USC has rejoined the SG, the USC determines it requires refueling. The USC and the refueling ship perform this operation after both dropping slightly behind the SG. Once refueling is complete, the USC rejoins the SG.

Mine neutralization in both mine hunting and mine sweeping is similar. Mine hunting was used in this scenario because more complex sensors are required and the sensor processing is more stressing to a USC.

1. USC navigates in formation with SG**
2. USC receives orders to perform mine search and clearance in littoral area in SG path
3. USC sprints ahead of SG to assigned littoral Op area
4. USC uses NAV and sensor data to calculate Op area for search and clearance**
5. USC performs mine search/threat detection using MIW module package

6. USC processes sensor data onboard in order to identify mines**
7. USC neutralizes mine threats using MIW module package**
8. USC scans area to verify threat neutralization
9. USC reports “all clear” for OPAREA.
10. USC continues navigation, rejoins SG
11. USC reaches low fuel level trigger and requests refueling
12. Replenishment oiler responds affirmatively to USC
13. USC initiates refueling routine, drops behind SG
14. USC recognizes and rendezvous with replenishment oiler and enters refueling mode**
15. USC disarms self defense measures as necessary for refueling
16. USC monitors refueling
17. Refueling is complete, replenishment oiler severs connections, navigates away
18. USC restores self defense measures and rejoins the SG

2. Scenario 2 – Submarine Scenario

A USC is navigating with a SG. During transit, the USC is performing protected passage operations. Once the strike group arrives at the operating area the USC performs maritime shield operations. After the maritime shield operation is complete, and the SG begins to navigate away from the Op area, the USC requests routine maintenance, and the request is granted. The USC navigates to the maintenance area, and receives maintenance. Once the maintenance is complete, the USC rejoins the SG.

Hold at risk operations and maritime shield operations are similar. Maritime shield operations were chosen because they are more complex than hold at risk operations.

1. USC navigates with SG
2. USC receives orders to perform protected passage for SG
3. USC initiates protected passage routine
4. USC navigates to area front of the SG
5. USC uses ASW package to monitor for submarines**
6. USC processes data and sends report to SG
7. USC ends protected passage routine when SG reaches target destination

8. A pre-set trigger is tripped or remote signal is received by the USC
9. USC initiates maritime shield routine
10. USC increases onboard submarine sensing
11. USC determines placement of sensor field for submarine detection
12. USC navigates to calculated locations and places sensors
13. USC monitors sensors for contacts
14. USC detects, localizes, and identifies contact using ASW module**
15. USC determines threat level of contact**
16. USC navigates to threat
17. USC engages threat using ASW module**
18. USC verifies threat neutralization
19. USC continues to monitor sensors
20. A pre-set condition is tripped or remote signal is received by the USC
21. USC ends maritime shield routine.
22. USC resumes navigation with SG
23. USC reaches maintenance trigger, generates report, and requests maintenance**
24. USC receives communications that maintenance request is granted
25. USC navigates to maintenance site and moors for maintenance, enters maintenance mode
26. USC disarms self defense measures as necessary for maintenance
27. USC will continue to monitor performance during/after maintenance to ensure proper maintenance is completed, tested, and reported
28. USC receives signal that maintenance is complete, checks against sensor data

3. Scenario 3 – USC Attacked and Damage Control Response

A USC is navigating alone to a rendezvous with a CSG. During transit, the USC encounters multiple small crafts. The USC attempts to avoid the small crafts and warn them to exit the area. The crafts attack the USC and causes damage. The USC neutralizes the small craft and performs damage control. The USC sends an incident report and navigates to home base.

1. USC is navigating alone and heading to rendezvous with CSG
2. USC senses small crafts heading towards USC
3. USC attempts to identify small crafts, concurrently sends info to command
4. USC determines that small crafts are not friendly by lack of Identification, Friend or Foe (IFF) personal identifier and intercept course
5. USC changes course to avoid encounter**
6. Small crafts change course to intercept
7. USC issues warning to small crafts
8. USC shoots warning shot off the bow of one of the small crafts**
9. Small crafts respond with firing missiles
10. USC defends self with maneuvering and attempted shooting down of small missiles
11. USC determines lethal force is acceptable**
12. USC engages attacking small crafts
13. USC assesses neutralization of small crafts
14. One missile from small crafts impacts USC, damage to port side auxiliary machinery space
15. USC assesses damage from missile impact**
16. USC engages damage control measures
17. USC reconfigures to minimize damage impact on ship systems**
18. USC assesses effectiveness of damage control measures, condition of equipment, once damage control is complete
19. USC completes an incident report and transmits to command
20. USC receives orders to return to home base for repairs
21. USC navigates to home base
22. USC docks at home base

23. USC receives maintenance

**Stressing situation for USC. These are steps where the autonomous capabilities will be tested as people are normally involved during these steps.

H. SUMMARY

The problem definition phase investigated the need for an autonomous USC and selected ASW and MIW as the military missions for the USC to perform. This section also developed constraints, a CONOPS, and functions for the system. The constraints were then allocated to the functions. Three operational scenarios (ASW, MIW, and self defense / damage control) were developed to identify actions that would stress an autonomous USC.

III. CONCEPT DISCUSSION

This section of the report discusses several areas of consideration for an autonomous USC concept. Relevant technologies for each functional area are addressed. Additionally, some top level physical architecture, design philosophy, and integration considerations are presented. Lastly, cost and risk considerations for USC construction and implementation are presented. The considerations in this section are presented as items to note in the future when a USC design occurs.

A. Relevant Technologies

a) *USC Central Control Architecture*

A USC should be an unmanned autonomous vessel that will be able to perform functions of all the elements of the Command, Control, And Communications Information, Surveillance, And Reconnaissance (C4ISR) systems. The C4 system should be comprised of the Command, Control, and Communication systems and by definition should include the facilities, equipment, communications, procedures, and personnel essential to a commander for planning, directing, and controlling operations pursuant to the missions assigned [DOD, 2011]. Since there will be no personnel or commander onboard a USC, C4 functions involving them will be performed as part of the autonomous, Artificial Intelligence (AI) function of the USC.

The ability of a USC to perform Intelligence, Surveillance and Reconnaissance (ISR) functions autonomously will be integral to achieving effective execution of its assigned missions. According to a study done on USC capabilities:

> "Intelligence is characterized as the collection, correlation, processing, and exploitation of data from various intelligence sources. Surveillance and reconnaissance are defined as the observation of airborne, surface based, or subsurface objects through visual, photographic, electromagnetic, or acoustic means. ISR will include the detection and monitoring of threat resources and their activities, as well as securing data concerning the meteorological, hydrographic or geographic characteristics of areas of operation.

> Intelligence operations can rely on clandestine means to search for and detect emissions; and to identify, localize and characterize their sources. Data will be exploited and intelligence derived through off-board processing systems in distributed collaboration with other intelligence systems and users.
>
> Surveillance and reconnaissance operations will use passive acoustic and electromagnetic sensors to collect data across a broad frequency spectrum. Signal processing of these emissions will provide the means for selecting, geo-locating, and tracking targets/objects of interest. The Unmanned Naval Surface Combatant (UNSC) will depend on a variety of sensors in this process, including sensors on UNSC-deployable unmanned vehicles."[Brady, 2004]

Figure 7 presents a high level architecture of the control functions that a USC should perform. This architecture is based on the DDG 1000 Total Ship Computing Environment (TSCE) [Anon17, 2006]. The Central Control Computing Center (4C) should perform many of the Command and Control (C2) functions and control the Ship Control functions, the Mission Systems Control functions, the Weapons Control functions, the External Communications Control functions, and the External Sensors Control functions.

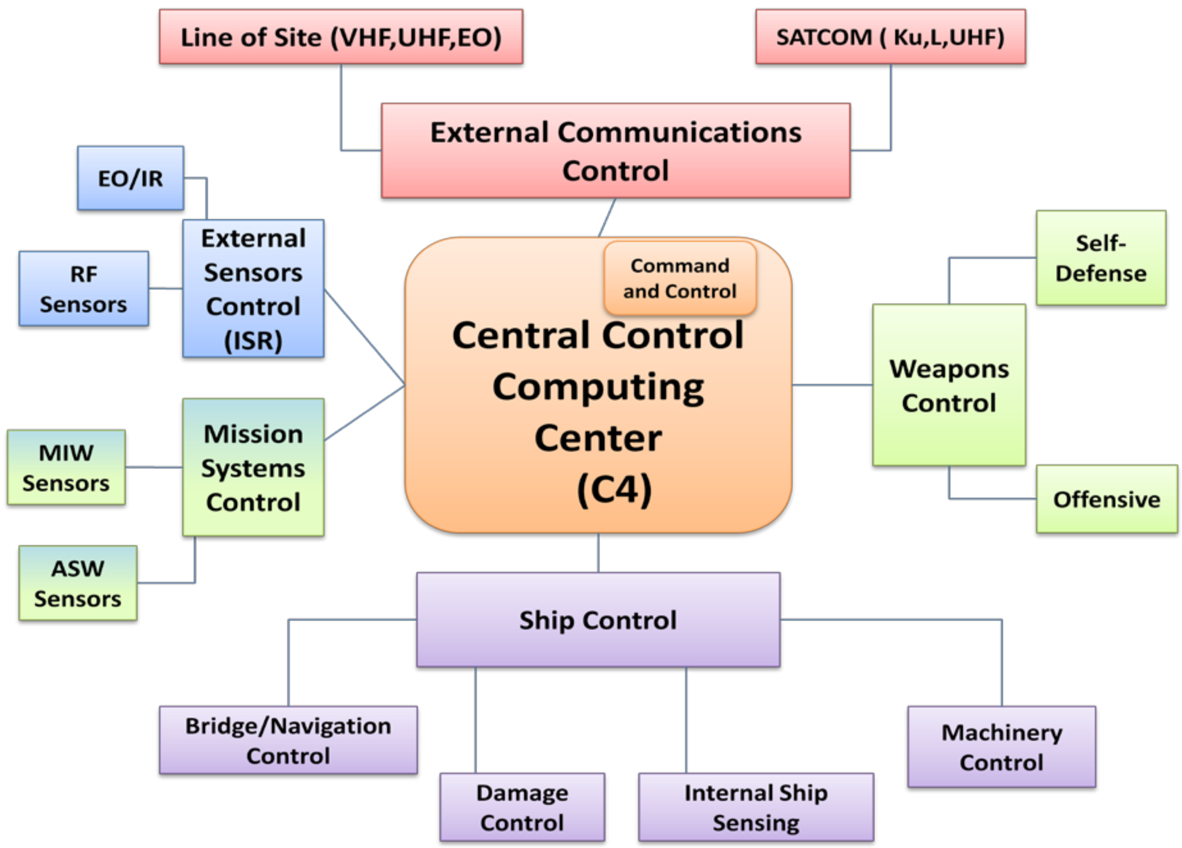

Figure 7. Potential USC Central Control Architecture

Central Control Computing Center

The Central Control Computing Center (4C) for a USC is the centralized processing unit for all actions the ship performs. In order to seamlessly accomplish required missions as well as keep the ship functioning for extended periods of time without human intervention, a high level of operational complexity will need to be developed and integrated into the 4C software. The development and testing of this enabling technology will be the most challenging aspect of achieving an actual USC design.

4C leverages a modern open system architecture and that architecture provides a scalable platform for cost-efficient delivery of new mission capability. In order to implement this architecture, 4C is divided into the following control and monitoring modules:

- Ship Control
- Mission Systems Control
- Weapons Control

- External Communications Control
- External Sensors Control

Ship Control

A USC Ship Control module will control and monitor all systems associated with Navigation, the Machinery Plant, Damage Control, and Internal Ship Sensors.

The Machinery Plant Control system will monitor, start, stop, and reconfigure all aspects associated with the propulsion plant, the electric plant and various other auxiliary machinery and systems.

The Bridge and Navigation system will provide the ability to receive and execute ship maneuvering actions. The system will perform all functions currently executed by the bridge crew on a manned combatant by employing a variety of sensors including cameras, navigation radar, Light Detection And Ranging (LIDAR), Global Positioning System (GPS), AIS, and environmental sensors (including but not limited to wind speed and direction, temperature, and weather radar).

Mission Systems Control

A USC Mission Systems Control module will be needed in order to control the command activity of the various MIW and ASW systems (both for shipboard sensors and deployed sensors/systems, if appropriate). The Mission Systems Control system will need to interface with the 4C system to provide the precise maneuvering required for any launch and recovery operations for MIW and ASW sensors, if so incorporated. Position, heading, depth, and speed of any offboard sensor would need to be strictly controlled to successfully conduct unmanned launch and recovery operations. A mine hunting towed body would need to be deployed via commands from this module, and any required detection/classification information would need to be downloaded to the module for processing and further assignment/upload to the mine neutralization body. Mine sweeping operations would also be controlled by this module.

Weapons Control

The USC will need to operate as part of a SG, or autonomously where it may be required to act defensively or offensively. The USC should have the ability to defend itself against above-surface, surface, and below-surface threats by using evasion, seduction, or hard-kill systems. This self-defense capability is needed because a fully capable USC is likely to be a costly asset, and it will often be operating without other forces which could normally provide defense. Offensive capabilities should include the ability to engage the same threats mentioned above. While no unit commander would be onboard the USC, at some point in the mission planning, implicit or explicit permission may need to be given to fire weapons. It is assumed that any weapons fire would have concurrence of the command and control authority located off-board. This authority may either be given as part of the mission plan that the USC is executing or part of the real-time commander's permission to fire. The move to fully autonomous lethal weapon employment would constitute a major change in naval policy, doctrine, or tradition, and would ultimately have to be addressed by high Department of the Navy (DON) and DoD commanders.

External Communication Control

This system is intended to allow a USC to transmit and receive information. Most of the communications would be used to perform the following:

- Receive Control Orders
- Receive material status traffic inquiries
- Receive operational status inquiries
- Receive local, automated ISR data
- Transmit/Receive tactical SA data (Link-11, Link-16)
- Transmit ship operational status
- Transmit radar, sonar, and EO/IR sensor data
- Transmit ship material status
- Perform navigation operations
- Control off board vehicles (e.g., other UV's)

External Sensor Control (ISR function)

The sensor suite should include onboard and offboard sensors and a data processing center that detects, classifies, and characterizes all objects and RF emissions within sensor range. The

sensors should monitor sub-surface, surface and above surface activity. Any type of unmanned vehicle networked with the USC would extend the range of the ship's sensors beyond line of sight.

Information from these sensors would be used to collect, process, and exploit data to enable the USC to accomplish its assigned missions. The sensors should include sonars capable of operating in both deep water and littoral water for subsurface threat detection as well as EO/IR imaging sensors for surface and above-surface threat detection.

A USC should be capable of performing autonomous ASW missions (tracking submarines) and MIW missions (mine hunting and mine clearing operations) in order to be effective. These two missions would require at least two distinct sonars. Mine hunting would require a high frequency sonar that provides high resolution for object identification. The ASW mission could use mid or low frequency sonar for detection of submarines. These could be towed, hull mounted or retractable over the side.

Significant programming would be required to enable a near term USC to use an autonomous external sensor suite. An additional consideration is the magnitude of data that would be collected, analyzed, sent and received by the USC. Keeping the data transmissions within bandwidth limits would require data analysis and reduction onboard the USC.

b) *Anti-Submarine Warfare*

Anti-Submarine Warfare (ASW) is one of two missions that was chosen as appropriate for a USC. Submarines, especially quiet diesel submarines, are a current and growing threat to US Naval Forces. Currently over 40 countries operate submarines [Anon, 2011], predominately diesel-electric, which are relatively cheap, quiet when running on battery power, and operate in the littorals. In October 2006 a Chinese 160ft Song Class diesel-electric attack submarine surfaced within five miles of the US aircraft carrier Kitty Hawk (CV 63) in the Pacific Ocean near Okinawa Japan. [Anon, 2011]. This incident is one reminder of why ASW is a critical mission area for the US Navy in general, and a notional USC in particular.

The purpose of ASW is to detect, localize, classify, track and engage subsurface targets. An effective ASW system must perform all of these tasks. In order to accomplish this it will require a group of components working together to resolve the ambiguities of underwater contacts. There is no single commercial system that performs all of these activities and no navy systems which perform all these activities autonomously. The complete spectrum of activities can be handled by a single vessel under the right conditions but usually is handled by several platforms working together. For instance, a US Navy surface combatant can deploy a towed array to detect a hostile underwater contact, a helicopter can subsequently be deployed using a dipping sonar, Magnetic Anomaly Detector (MAD), or an air-launched-sonobuoy to confirm and localize the contact, and a P-3 ASW aircraft can be brought to use its ASW sensor suite to obtain bearing and heading information. All the data obtained can then be assembled, synthesized, and analyzed; based on prevailing circumstances a decision is made as to which platform and what weapons are used to neutralize the contact.

Implementing an autonomous system requires synthesizing all the data generated by the various onboard and offboard sensors into a decision making software system (e.g. artificial intelligence) that would inform future ASW actions. The complexities of the underlying systems, the amount of data, and the data rate of the sensors all ensure that automating an ASW system would require a significant software development program. In addition, before allowing an unmanned vehicle to fire lethal weapons, the targeting and weapons release authority procedures must be developed, tested, approved, and certified and rules of engagement developed. These components will also interface with navigation, self defense and mine warfare. The major components required for an ASW system are described below. Details of these component technologies are in APPENDIX E – ASW TECHNOLOGIES.

Visual Detection

Visual detection by a human aboard a surface ship is the oldest detection technique and remains a viable option for submarine detection. Visual detection usually results from a submarine surfacing, or coming to periscope depth where the periscope or periscope wake is visible. However, under the right conditions, a submarine at shallow depth can be tracked even at night by the blue green glow of bioluminescence in its wake, light emitted from certain species of

dinoflagellate plankton when disturbed by a moving vessel. Submarines can also be detected by aircraft when the periscope or periscope wake, called a scar, is visible on the surface. Also, when submarines are submerged against a light colored bottom surface and are in clear water, they can be spotted by aircraft, even those not engaged in ASW. Therefore, an electro-optical, Forward Looking InfraRed (FLIR) or other system which can recognize these visual cues could be used on a USC in place of a human presence.

Hull Mounted Sonar

A USC performing ASW operations will require a hull mounted sonar with both active and passive capability in order to detect, localize, classify and track subsurface contacts. The preferred ASW system should utilize Commercial Off The Shelf (COTS) components and open architecture to the maximum extent possible. This would avoid locking the USC into a proprietary architecture that limits the ability to incorporate advances and increased computing power. A good example of this approach is the AN/BQQ-10 Advanced Rapid COTS Insertion (ARCI) combat system used on SSN submarines. It is able to receive more frequent scheduled updates to system capabilities as well as quick delivery of advanced functions to the fleet at a reduced cost.

A modular sonar system would also allow for rapid upgrades and customization of the ship for specific missions. Since a USC is unmanned by definition, critical systems must demonstrate an extremely high reliability, which infers utilization of simple, redundant, and mature technologies.

Towed Array

A towed array can be both active and passive and is used to detect, localize, classify, and track submarines. There are two types of towed arrays: a linear array that is towed behind a ship at a single fixed depth related to the buoyancy of the array, and a variable depth sonar that can be controlled such that it can be towed at various selected depths. In the ocean the main factor affecting sonar performance is temperature, which varies with depth. This temperature change called the thermocline refers to the water layer that divides the warm surface water and the cold deep waters. A sound originating from one side of the thermocline tends to remain on that side

since it is reflected off the boundary layer. A very loud noise like active sonar, firing weapons, explosions etc. can cross the boundary layer. Seabed terrain and composition, pressure, salinity, and water turbulence can also affect sound propagation. A towed array would allow a USC to listen below the thermocline while the hull mounted array would listen above it.

Linear Array

A linear array is towed well behind the ship which provides an opportunity to get beyond ship noise and listen more effectively. However, since most arrays have no directivity built in, it is difficult to distinguish where sounds are coming from (i.e., left or right).

Variable Depth Sonar

To overcome the difficulty of hunting or listening for submarines that take advantage of hiding in thermoclines, a variable depth sonar (VDS) can be used. A VDS is designed for active or passive operation. It is designed to detect, classify, and localize submarines at safe stand-off distances. The transducer array, digital transceiver and various sensors are integrated into a towed body which transmits data to the ship for processing. Most VDS' are designed for deep ocean use but newer models are available with higher frequencies better suited to littoral uses.

Sonobuoys

A sonobuoy is another device used in conjunction with towed arrays to detect, localize, classify, and track a submarine. A sonobuoy is a relatively small expendable sonar system that can be dropped or ejected from aircraft or ships. Upon entering the water, the sonobuoy activates, performs its function and then the device scuttles itself. The sonobuoys provide a deployable acoustic signal source and they collect underwater signals of interest. These received signals are transmitted to monitoring unit(s) that process the signal for analysis, classification of target, and recording for replay and post event analysis. Sonobuoys allow for short and long range detection of surface ships and submarines. There are three categories of sonobuoys: active, passive and special purpose. Sonobuoys are expendable devices and due to their low cost and ease of

deployment, all existing sonobuoy types could be used by a USC based on mission requirements. Minimal development would be needed to autonomously eject these devices from the ship.

c) *Mine Warfare*

Mine Warfare was the second military mission chosen to be appropriate for the USC. Mines are a serious threat to US Naval Forces, and in light of current world enemies they are particularly concerning because they are relatively cheap to field and can cause severe damage.

Before the advent of sonars and other advanced technologies, explosive ordnance teams were the only method of searching out and defusing or detonating mines. This was a very time consuming and dangerous operation. Marine mammals were eventually trained to perform missions faster and with less harm to humans. While both of these methods are still used in certain cases, technology has allowed mine operations to go much faster without as much danger to people.

Mine warfare today ideally consists of mine hunting (detect, classify, and identify mines) coupled with mine neutralization. A mine hunter will generally be launched from a vessel and towed by an Unmanned Underwater Vehicle (UUV) or towed behind a helicopter. Sonars on the mine hunter will detect the mine and then an onboard processor (or a processor on the towing platform depending on chosen towing system) will classify and identify the mine. At that point, the mine hunter will be recovered and a neutralizer pod will be deployed and towed by a helicopter. The neutralizers are launched from the pod and guided by a human to the mines, at which point they are neutralized. When hunting is not feasible (i.e., the terrain is too rocky or littered with debris), a mine sweeper will be towed by a helicopter or USV, depending on the system, and will generally use acoustic influence to neutralize the mines. Besides being a very important mission capability area, mine warfare is apt for integration with a USC since it takes people directly out of harm's way and technologies are now maturing which are already partially autonomous.

MIW Relevant Technologies

Several current fielded or developmental technologies in the areas of mine hunting/neutralization and mine sweeping were researched. Descriptions of each technology are listed in APPENDIX C – MIW TECHNOLOGIES. These technologies were considered to be a baseline upon which more research and development could take the systems to full autonomy for use onboard a USC. Some enabling technologies apply across the board to mine hunting, neutralization, and sweeping. These are:

- Automatic target recognition – algorithms that make decisions. The mine hunting/sweeping/neutralizing systems have to know what environment they are in – this technology is close but not there yet.
- Post mission analysis – this is all manual right now and it could/should be automated.
- Automated mission planning – the systems need to be able to re-plan in real time.
- None of these systems have obstacle avoidance right now
    - Planned vs. unplanned (2 types of avoidance)
    - Remote Minehunting System (RMS) did obstacle detection, but not avoidance
- Launch and recovery
    - The Remote Environmental Measuring UnitS (REMUS) has done docking underwater
    - Launch and recovery systems exist but this is a major challenge in a totally unmanned environment

Required relevant technologies which are specific to mine hunting, neutralization, or sweeping are described in the following sections:

Mine Hunting

Current systems are able to provide full mine reconnaissance capability including detection, classification and identification. Systems currently fielded are towed from a helicopter or UUV. Newer systems which are actually fixed to the helicopter have been developed, leveraging the height of the helicopter above the water to provide a broad swath view, which allows the system to cover more surface area in a shorter period of time. However, this also means it will need to remain an airborne system so it will need to be deployed via an unmanned platform such as the Vertical Take Off and Landing Tactical Unmanned Aerial Vehicle (VTUAV). Adding an Unmanned Aerial Vehicle (UAV) to a USC would add complexity, cost and weight, but also

increase capability. Another aspect of mine hunting which needs significant work to become fully autonomous is environment classification. Mines are difficult to identify in cluttered environments and mine sweeping is often used as a backup.

Mine Neutralization

Mine neutralization systems can either be deployed by ship or helicopter, so they would not need excessive physical adaptation to a USC. As with any system deployed autonomously, launch and retrieval will be a significant challenge. Neutralizers are self-propelled but guided by a person and then detonated once the mine comes into view. In order to have a fully autonomous system, the neutralizer would need to be able to navigate itself to the target and correctly identify the mine prior to detonation.

Mine Sweeping

Influence mine sweeping systems can be towed at high-speed from helicopters or USVs. Since the host in this case is unmanned, this system may already have some mechanisms which would aid launch and retrieval, though autonomous operation still presents additional challenges. Of the three systems, it is the closest to full autonomy.

Note that there is some preliminary work on a system which would combine the hunting and neutralizing functions into a "one-pass" mission system. If this system is successfully developed, time due to launch, retrieval, and processing of multiple systems would be significantly reduced.

d) *Navigation*

Navigation is critical for any ship but there is a difference between navigation in the traditional sense and tactical navigation required for a combatant ship. A USC will need to maintain precise navigation and maneuver in formation. Traditional navigation is primarily focused on safely maneuvering the ship while in transit from point A to point B. Absolute position is required to guide the ship. On the other hand, tactical navigation is not focused on simply maneuvering the ship in navigable waters by determining its absolute position. In this context, a USC must also be

able to determine its location relative to the locations of friendly or hostile contacts, whether they are on the surface, below the surface, or in the sky. Autonomous navigation requires a highly integrated navigation system that fuses data for surface, subsurface and air contacts and presents a unified picture of the situation including identification of the relative locations of all contacts.

With the large amount of data generated by the various sensors, the processor must monitor the stream of data, prioritize required actions and monitor changes to determine subsequent action needed on a continuous basis. Several enabling technologies are fundamental to successful autonomous navigation (further details provided in APPENDIX D – NAVIGATION TECHNOLOGIES). These include:

- An Automatic Information System (AIS) similar to Identification Friend or Foe (IFF) used in aircraft. AIS provides ship to ship identification and additional information that can be used to prevent collisions, although this is required only for larger ships.
- Obstacle avoidance (in accordance with COLREGS) and collision avoidance. The USC must be able to maneuver both in concert with the fleet and independently, while adhering to the nautical rules of the road to avoid stationary and moving objects.
- Day/Night all weather vision – without humans aboard, the visual system must be able to identify contacts 24/7 especially in adverse weather when wave height and ship pitch and roll could degrade sensors.

Several currently fielded or developmental autonomous navigation technologies were researched and are presented in Appendix D.

e) *Self Defense*

One assumption is that a fully capable USC would be a naval platform of considerable cost and usage, and as such, must have the capability to defend itself against attack for self preservation as well as to defend other allied forces, should the occasion arise. Self defense requirements for a USC should include detecting, identifying, tracking and engaging air targets and surface targets in defense of the USC with anti-air, anti-surface, and soft kill weapons. Self Defense

requirements for a USC should be similar to surface combatants, but aimed more at protecting property only and not personnel.

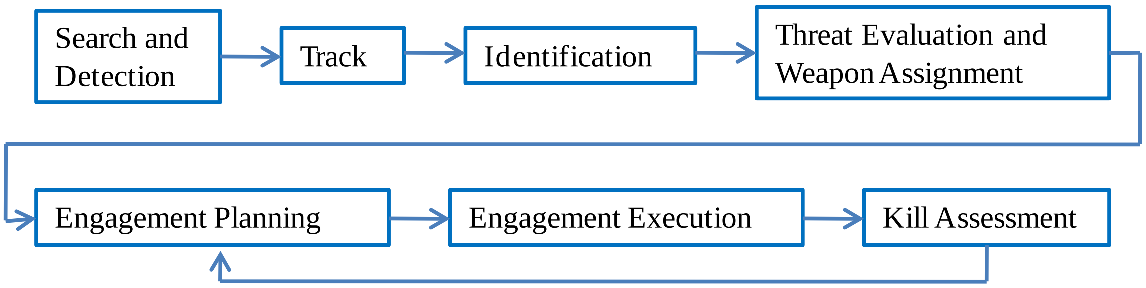

Figure 8. Engagement Sequence After [Huang, 1994]

Figure 8 is a typical threat identification and engagement sequence, taken from “An Autonomous Optimal Weapon Assignment Algorithm for Ship Self Defense” [Huang, 1994].

The following Detect to Engage description is derived from Naval Academy training information posted by the Federation of American Scientists website [Anon7, 2011].

> “Detecting the Target
>
> There are three phases involved in target detection by a weapons system. The first phase is surveillance and detection, the purpose of which is to search a predetermined area for a target and detect its presence. This may be accomplished actively, by. ..radar, and/or passively, by receiving energy being emitted by the target, as by ESM ... The second phase is to measure or localize the target's position more accurately and by a series of such measurements estimate its behavior or motion relative to own ship... Finally, the target must be classified, that is, its behavior must be interpreted so as to estimate its type, number, size and most importantly identity…
>
> Tracking the Target
>
> … To successfully engage the target and solve the problem, updates as to the target's position and its velocity relative to the weapon system must be known or estimated continuously. This information is used to both evaluate the threat represented by the target and to predict the target's future position and a weapon intercept point so the weapon can be accurately aimed and controlled…

… The modern "battlefield" is one in which sensors are detecting numerous contacts, friendly and hostile, and information is continually being gathered on all of them. The extremely high speed, precision, and flexibility of modern computers enable the weapons systems and their operators to compile, coordinate, evaluate the data, and then initiate an appropriate response. Special-purpose and general-purpose computers enable a weapons system to detect, track, and predict target motion automatically. These establish the target's presence and define how, when, and with what weapon the target will be engaged.

Engaging the Target

Effective engagement and neutralization of the target requires that … a warhead, be delivered to the vicinity of the target. How close to the target a warhead must be delivered depends on the type of warhead and the type of target…"

Solving the fire control problem from target detection to neutralization requires a complex integration of numerous components. Weapon system software is needed to perform this integration.

Attributes of Self Defense Capabilities

Attributes of Self Defense capabilities are discussed below. Detailed technology descriptions are included in APPENDIX F – SELF DEFENSE TECHNOLOGIES.

Identification of Surface Targets – It will be difficult for a USC to identify friend or foe and subsequently make decisions regarding whether and when to employ deadly force.

Identification of friendly forces should be, in most cases, simple and is aided by current systems such as AIS (Automatic Identification System) and LRIT (Long Range Identification and Tracking system). However, AIS can also be easily reprogrammed to ID merchant vessels vice naval vessels.

Identification of hostiles will be difficult for a USC. Currently, visual surveillance and verbal interrogation/communication are used. A USC would need visual input from long range, all weather day and night video cameras with panning and zooming capabilities. Software would then interpret data from the video camera in order to identify known pirate ships or the presence of weapons, etc. The USC would need methods of long range communication, at least one-way with translation using radio or a long range acoustic device.

Once a hostile is identified, the USC could choose between evasion, issuing a warning, attack with a non-lethal weapon, or warning shot off the bow. Due to ethical issues of unmanned systems, lethal weapons should be used only as a last resort and only when remotely ordered by a strike group commander.

Air Threat Evaluation and Weapons– A USC will need guns or missile systems to defend against air targets. The weapons system needs to be able to assess incoming threats based on speed and heading. The ship should also be equipped with ESM, electronic countermeasures (ECM), chaff, and decoys. Software should choose the optimum weapon since chaff and decoys are much less expensive than offensive rounds, which would also be limited by automated magazine capacity. Since this is an unmanned ship, the extra risk taken in not engaging with hard kill weapons may be warranted based on predicted effectiveness of the soft kill weapons.

Lethal Weapons – A USC should have lethal weapons such as guns and missile launchers to defend against all lethal threats targeted at itself or allied forces in its vicinity. The best choice of weapon would be short to medium range, lightweight (to fit a compact and fuel efficient design), and able to be self loading or pre-loaded with automatic rounds or use replenishable ammunition such as laser weapons with a continuous energy supply.

Non-Lethal Weapons – Since a USC needs to act autonomously, it is crucial that there are non-lethal weapons alternatives, such as acoustic devices and tear gas, which can and should be used first if possible. Non lethal weapons need to be long range, guided/aimed by radar, and automated.

f) *Damage Control*

The approach to damage control for a USC would be similar to damage control for a manned surface combatant, but the lack of shipboard personnel presents advantages and disadvantages that affect the material solution selection process.

For example, there is no need for a fire party to set damage conditions. Since there is normally no need for personnel access to the different compartments on the unmanned ship, watertight closures can be kept secured at all times to maximize ship safety and integrity, and prevent the spread of flooding or fire. Vent dampers can be closed immediately and automatically by ship controls to prevent fire spread, should one occur, without the risk of endangering personnel.

On the negative side, the lack of personnel will require more system sophistication to monitor, detect and react appropriately to damage control scenarios. A tactical approach to fighting small fires without using portable extinguishers and hose reel stations may need to be devised using telerobotic nozzles (as used on DDG1000), to keep space fire fighting such as AFFF sprinkling to a minimum and avoid water intrusion, corrosion issues, and discharge of AFFF especially close to shore.

Attributes of Damage Control Capabilities

A USC will need to implement the following automated damage control functions should there be damage to the ship caused by internal or external factors:

- Fire Prevention and Control
- Flooding Control
- Ship Damage Recognition and Prediction
- Under hull Monitoring
- Intrusion Control

Detailed technology descriptions are included in APPENDIX G – DAMAGE CONTROL TECHNOLOGIES.

Fire Prevention and Control

A USC will need to prevent, detect, and extinguish the following classes of fires common on US Navy ships:

Table 12. Fire and Extinguisher Classes

Class	Source	Normal Extinguisher
A	Ordinary Combustibles	Water (firemain, mist)
B	Flammable liquids or gases	CO2, Halon, FM200, AFFF
C	Electrical Equipment	FM200, CO2, PKP

Table based on Standard Fire Classes

Flooding Control

Consistent with other Navy ships, a USC will need to be designed for flooding control with physical watertight boundaries. Flooding sensors will need to be installed, and the USC will need to have an automated means of dewatering should there be a hull breach and water ingestion.

Ship Damage Recognition and Prediction

Because there would be no damage control party to restore the ship to its normal operating condition, the USC would need to have a method for damage assessment and damage recovery. Damage assessment includes monitoring sensors of all critical equipment, and cameras for remote general assessment of damage. Damage recovery, such as starting standby equipment, will need to be automated and enabled with emergency power. Damage recovery will also depend greatly on designing the ship electrical and Local Area Network (LAN) systems to be reconfigurable with redundant equipment and paths.

Underhull Monitoring

Underhull monitoring will be required to ensure the security of a USC, especially in port, and can be accomplished with hull mounted equipment or an unmanned underwater vehicle.

Intrusion Control

Security at the pier (as well as at sea) will need to be taken into account to avoid unwelcome entry, and can be accomplished with cipher locks and/or smart card entry. Because it is an unmanned ship, cameras with facial recognition could be used in case of tampering, along with methods of dealing with perpetrators (such as tear gas or retracting floors). Secure spaces will need extra security measures such as secure data protection and, if necessary, destruction.

B. Top Level Physical Architecture Discussion

The scope of this project was limited by time, resources (ship design tools/software) and the skill sets of the Capstone Group participants (i.e. lack of naval architecture expertise), therefore, various physical architectural options were not seriously considered or designed for evaluation. However, based on the selected USC operational constraints and functions, some physical architecture considerations can be discussed to offer some perspective if further design and evaluation in this area were to occur:

- Draft - The vessel draft will need to be limited to adequately operate in littoral waters and perform MIW. Typical drafts for similar vessels with this operational constraint have drafts that are less than 15 feet.
- Length - The vessel length will need to be limited to permit adequate maneuverability of the vessel during MIW operations. Typical lengths for similar vessels with this operational constraint have lengths ranging from 188 to 378 feet.
- Hull Material - The hull will need to have a low magnetic signature thus affecting the hull material selection and/or requiring a degaussing system.
- Propulsor - The propulsor will need to have high maneuverability and low noise performance characteristics to perform MIW and ASW operations.

Table 13. Applicable Surface Ship Dimensions

Ship Class	Hull Form	Length	Draft	Beam
MHC 51	Monohull	188 ft	11 ft	38 ft
LCS 1	Monohull	378 ft	12.8 ft	57.4 ft

VISBY	Monohull	236 ft	7.9 ft	34 ft

Since the proposed USC concept is a multi-mission platform required to perform a multitude of functions autonomously and unmanned, this will require a number of supportive systems with high redundancy and reliability in order to execute the primary missions. The trade-off of payload (for primary mission packages) versus the draft and length limitations will present some challenges to the design of the overall physical architecture. The hull material and propulsor selections will potentially present design and cost issues since they will probably require the design integration and production of material solutions that are not typical of the U.S. Navy ship industrial base.

It should be noted that a notional physical architecture concept in Appendix H was created based on considerations above and functionally similar vessels (i.e. LCS, MHC, and Visby) to create some additional context when evaluating the USC technologies and to show a possible material solution albeit one with a minimum of applied ship design practices.

C. Design Philosophy, Maintenance, and Refueling

Expanding on the previous discussion of Top Level Physical Architecture, additional design considerations, maintenance and refueling will be discussed here to offer further perspective if a future USC design effort were to be undertaken.

a) *Design Considerations*

The design of all vessels could benefit from an open architecture design approach. Open architecture permits the addition, replacement and swapping of system components with relative ease. This is extremely beneficial to a USC and should be leveraged as much as possible during design to minimize maintenance downtime and to allow for mission planning flexibility.

Maintenance will be a challenge for a USC since personnel will not be onboard the vessel during operational periods, therefore periodic maintenance will be severely or critically limited. An emphasis on an open architecture design will permit system components to be swapped out so that maintenance and repairs can be done without unnecessarily delaying USC operational availabilities.

Mission planning flexibility can be accomplished with an open architecture design approach. For example, a USC could have a Modular Mission Area arranged so that ISO container sized modular mission packages can be placed in various locations throughout. This offers the advantage of flexible mission planning and allows for future technological upgrades as it is very difficult to predict what weapon, combat and ISR systems will look like in 2020. Particularly with the dramatic advances in electronics, and the increased reliance on electronics in weapon, combat, ISR and even auxiliary systems, it would be difficult to develop ship concepts for this timeframe without making potentially highly inaccurate assumptions regarding the characteristics of these systems. Also, because a USC will support a variety of missions, a common platform capable of being rapidly reconfigured to support any of these missions provides operational flexibility as well as logistics and support simplicity. Accommodating "true" plug and play modularity will have a variety of benefits.

Another example where open architecture would be particularly beneficial to a USC would be the possible usage of fuel cell technology which is very adaptable due to its modular design. The US Navy Shipboard Fuel Cell Program is currently developing an Advanced Full Scale Modular Fuel Cell System Design for multi-platform applications. All the major fuel cell technology components (i.e., fuel cell stacks, fuel reformers and sulfur removal) will be modularized, making the system adaptable to ship platform mission needs. The goals are that fuel cells are able to operate in all Navy environmental conditions and fuel cell system modules are reconfigurable to meet various ship space considerations.

b) *Maintenance*

As discussed above, a more effective maintenance plan for a USC will require an open architecture design to allow quick and complete replacement during port availabilities.
For example, repairs to a disengaged module can occur after the USC has re-launched. Areas that are not modular, such as the hull, will need urgent maintenance during the availability. However, the interior modular components would be entirely removed from the critical path of the port availability.

Another potential benefit to modular repair outside of the scheduled availability is the balance of the workload for the maintenance personnel. Maintenance schedules would become more balanced as work that must occur during the availability decreases while work in between availabilities increases. For the majority of ship availabilities, the US Navy does not operate as described above. Additional planning and training on the part of the maintenance personnel would be necessary to successfully carry out this potential USC maintenance concept.

Additionally, maintenance while underway would be less extensive than in port maintenance. For example, a logistic support vessel could moor with the USC while underway. Maintenance crews from those vessels could access a workshop and spares area on the USC to get parts for repair. The workshop spares area could prioritize space for unique components for the USC ship because common components could be kept on the support vessel. That said; maintenance crew access to ship areas could be very limited since the USC design may not have a general arrangement that has the accessibility of a typical manned vessel design. The modules onboard

the USC would need to be arranged such that less robust components are situated in areas that the maintenance crews can access while a USC is underway. Lastly, redundant systems could reduce the need to perform urgent maintenance if a single system failed.

c) *Refueling*

Refueling while underway is a stressing capability for a USC concept. Technologies for unmanned ship refueling have not reached an acceptable TRL. It is quite possible that the Navy's Standard Tension Replenishment Alongside Method (STREAM) will not be adaptable for an unmanned vessel and that refueling will have to be performed by a manned crew from a replenishment oiler once the oiler has moored with the USC.

Another possible refueling option to consider, if the risks involved with mooring two ships wanted to be averted, fuel hose could be unreeled from the a USC and allow the replenishment oiler to secure the hose and initiate refueling. However, if a USC has achieved the capability for mooring with other ships due to a requirement to receive maintenance while underway, then opting for a simple connection on the USC exterior will likely suffice. Therefore, the likelihood of risk of failure during refueling due to a USC issue would be extremely low. Because of the importance of underway refueling, the reduction of risk for this capability is paramount when considering design alternatives.

D. System Integration Considerations

Up until now, the USC subsystem characteristics have been discussed separately. In reality, there will need to be integration between all of the subsystems. The team decided to use an integration philosophy similar to the DDG-1000 where the Central Control Computing Center (discussed in III.A.a)) subsystem is central and communicates with all of the other physical subsystems. The following is the total ship integration diagram showing relationships between the Central Control Computing Center subsystem and the rest of the major subsystems. The faint lines between each of the subsystems denote a back-up communication system, and fail safe and graceful degradation mode, should the central system become inoperable.

Figure 9. USC Total System Integration Diagram

Some effort was made to look at the communication paths between the Central Control Computing Center and the rest of the components, based on the USC operational scenarios. The following series of diagrams (figures 10 through 12) show these communications. Arrows denote which system is sending/receiving the information.

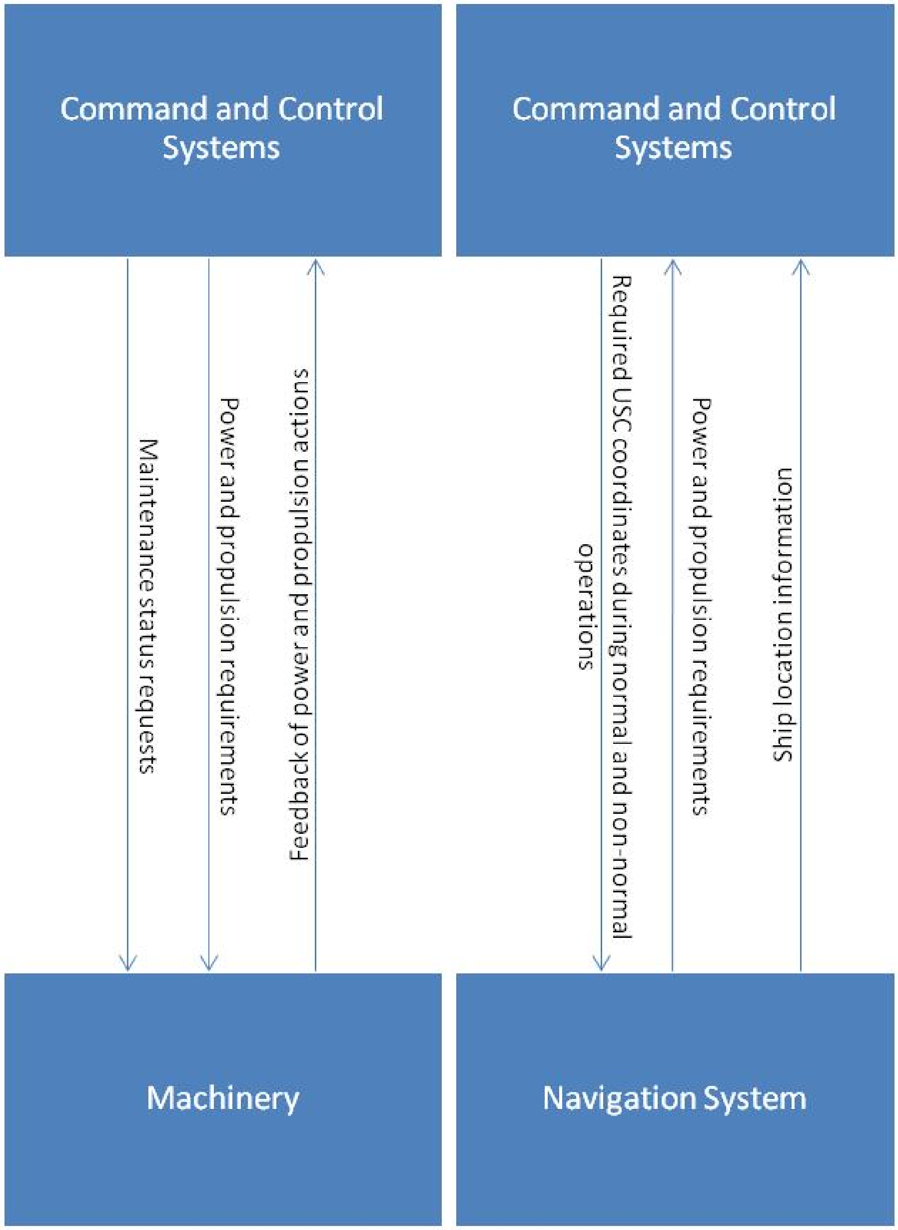

Figure 10. 4C Communications with Machinery and Navigation Systems

Figure 11. 4C Communications with Self Defense and Damage Control Systems

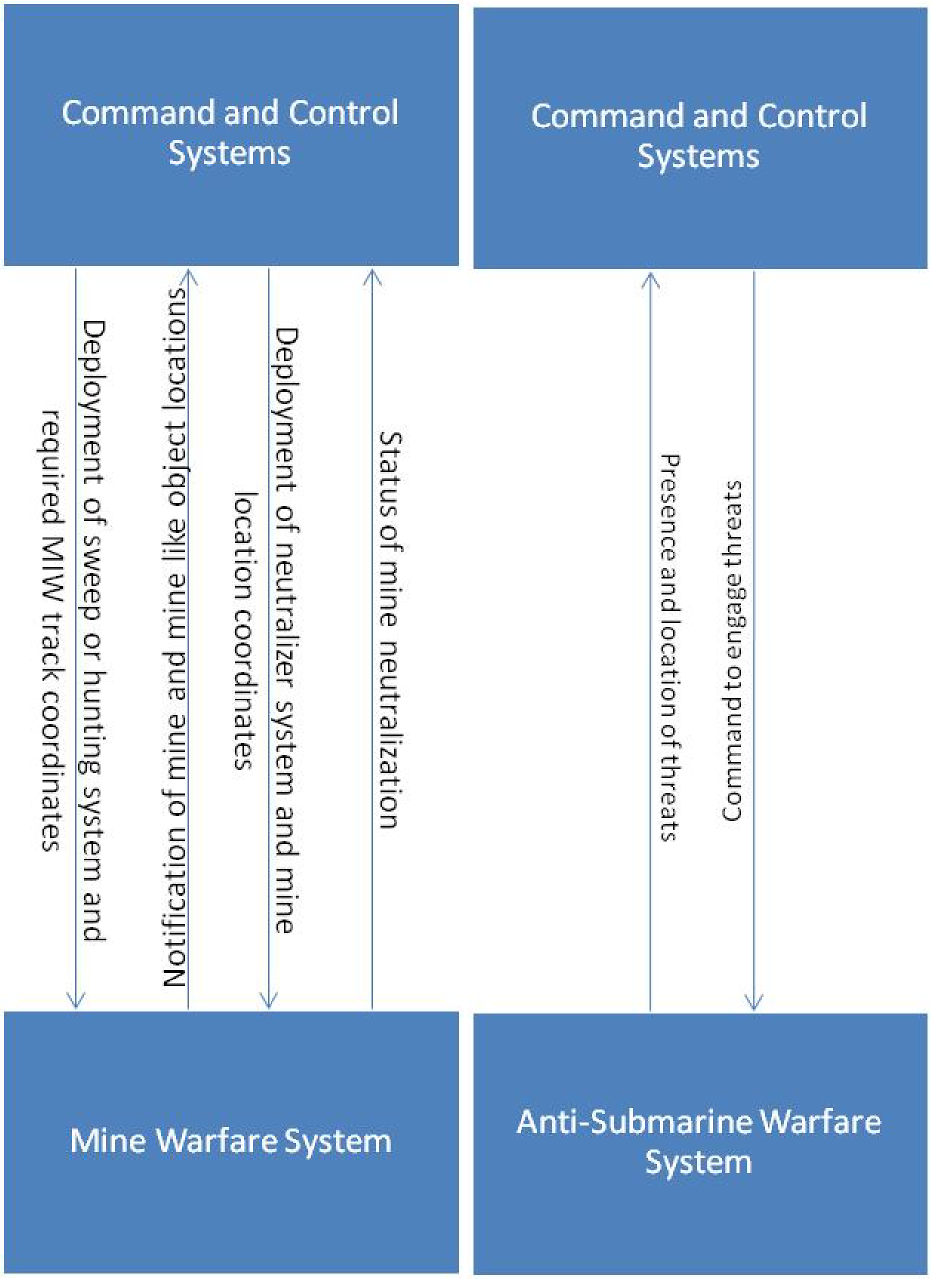

Figure 12. 4C Communications with MIW and ASW Systems

While the communications expressed in the above figures are general, more specific communications paths can be expressed for each of the USC operational scenarios to show subsystem linkages. One example of this is shown below in the Mine Warfare operational scenario:

1. USC navigates in formation with SG**
    - Communication between 4C and Navigation system: USC coordinates with respect to battle group and obstacle detection and avoidance
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
2. USC receives orders to perform mine search and clearance in littoral area in SG path
    - Communication from battle group commander to USC (outside of system boundary): Permission to break formation
    - Communication from 4C to MIW Module: Ready MIW systems for deployment
3. USC sprints ahead of SG to assigned littoral Op area
    - Communication between 4C and Navigation system: Coordinates for littoral Op area
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
4. USC uses NAV and sensor data to calculate Op area for search and clearance**
    - Communication between 4C and Navigation system: Coordinates for MIW clearance
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
5. USC performs mine search/threat detection using MIW module package
    - Communication between 4C and Navigation system: Coordinates and obstacle avoidance
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
    - Communication from 4C to MIW Module: Deploy and retrieve MIW minehunting/minesweeping systems
6. USC processes sensor data onboard in order to identify mines**

- Communication between 4C to MIW Module: Download of classification data minehunting/minesweeping systems

7. USC neutralizes mine threats using MIW module package**
    - Communication between 4C and Navigation system: Coordinates and obstacle avoidance
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
    - Communication from 4C to MIW Module: Deploy and retrieve MIW neutralizing systems
8. USC scans area to verify threat neutralization
    - Communication between 4C and Navigation system: Coordinates and obstacle avoidance
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
    - Communication between 4C to MIW Module: Upload target pictures and neutralization coordinates
9. USC reports "all clear" for OPAREA.
    - Communication from USC to battle group commander (outside system boundary): Mine field cleared
10. USC continues navigation, rejoins SG
    - Communication between 4C and Navigation system: Coordinates and obstacle avoidance
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
11. USC reaches low fuel level trigger and requests refueling
    - Communication from USC to oiler (outside system boundary): Refueling required
12. Replenishment oiler responds affirmatively to USC
    - Communication from Machinery system to 4C: Low fuel status
    - Communication from oiler to USC (outside system boundary): Refueling Request Accepted
13. USC initiates refueling routine, drops behind SG

- Communication from oiler to USC (outside system boundary): Refueling Request Accepted
- Communication between 4C and Navigation system: Coordinates and obstacle avoidance
- Communication between 4C and Machinery system: Required propulsion/engine output, and system status

14. USC recognizes and rendezvous with replenishment oiler and enters refueling mode**
    - Communication between 4C and Navigation system: Coordinates and obstacle avoidance
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
    - Communication between oiler and USC (outside system boundary): Mooring status
15. USC disarms self defense measures as necessary for refueling
    - Communication from 4C to Self Defense system: Disarm self defense measures
    - Communication from Self Defense system to 4C: Self defense disarmed
    - Communication between oiler and USC (outside system boundary): USC ready for refueling
16. USC monitors refueling
    - Communication between 4C and Machinery system: Fuel status
17. Refueling is complete, replenishment oiler severs connections, navigates away
    - Communication between 4C and Navigation system: Coordinates and obstacle avoidance
    - Communication between 4C and Machinery system: Fueling complete
    - Communication between oiler and USC (outside system boundary): Ships un-moored
18. USC restores self defense measures and rejoins the SG
    - Communication between 4C and Navigation system: Coordinates and obstacle avoidance
    - Communication between 4C and Machinery system: Required propulsion/engine output, and system status
    - Communication from 4C to Self Defense system: Arm self defense measures

- Communication from Self Defense system to 4C: Self defense armed

Identifying communication paths also helps with the integration of the various functional systems. Overlaps across subsystems are identified as well as potential gaps in capability (i.e., should torpedoes be assessed as part of anti-submarine warfare or as part of self-defense). Developing the systems integration diagrams clarifies the interactions between each of the functional areas, and assures a consistent level of abstraction across subsystems.

As previously stated, a notional physical architecture concept in Appendix H was created based on these integrated functions and this provides some additional context for evaluating USC functional integration. For example, this highlights which systems could be eliminated as a result of having no people onboard, and which systems would need the most access while underway or in port.

E. COST CONSIDERATIONS

In evaluating the cost of a USC, considerations need to be made for reduced costs from manning reductions, as well as increased costs from automation and additional reliability requirements of software as well as hardware from a lack of onboard maintenance.

Current US Combatant Costs:

The current R&D (total R&D divided by number of ships in the class), Procurement and Personnel costs of US surface combatants is represented in the table below (based on 2010 numbers in Congressional Budget Office (CBO) Letter to Senate dated 28 Apr 2010):

Life-Cycle Cost (Lifetime cost per ship in Million Dollars)					
Ship Class	**MCM-1**	**FFG-7**	**DDG-51**	**CG-47**	**LCS-1**
(Years)	30	30	35	35	25
R&D ($M)	3	2	72	8	20
Procurement ($M)	274	662	1484	2014	680
Personnel ($M)	**243**	**510**	**897**	**1156**	**161**

Below is the personnel make-up of each ship, calculated by CBO using 5-year average numbers out of the Navy's Visibility and Management of Operating and Support Costs (VAMOSC) system:

Personnel makeup (average per Ship)	**MCM-1**	**FFG-7**	**DDG-51**	**CG-47**	**LCS-1**
Officers	8	11	24	24	11
Enlisted	76	170	254	340	43
Total	**84**	**181**	**278**	**364**	**54**

From the information above, the following average yearly cost of personnel can be derived:

Ship Class	**MCM-1**	**FFG-7**	**DDG-51**	**CG-47**	**LCS-1**
Average Personnel Cost Per Ship Per Year (Million Dollars)	8	17	26	33	6

The personnel costs in the table above include current and future pay and benefits (including withholding taxes paid by the government, housing benefits, tax advantages, and veterans' benefits) of an average officer and average enlisted crew member, multiplied by the average number of officers and enlisted personnel in a ship's crew [Elmendorf, 2010].

For the five classes of ships listed here, personnel costs amount to an average of 18 million dollars per year, a significant expenditure for the Navy. Considering this cost on current surface combatants, an opportunity exists to save life cycle costs if personnel can be eliminated from the ships .

<u>USC Savings</u>:
A full multi-mission capable USC has the potential to replace some of the less capable surface combatants and save part of the personnel costs above. Actual cost savings will depend on how many personnel are needed to remotely monitor and control the USC, as well as potentially, additional support personnel who can maintain the USC's in each applicable region. If the USC does not need constant monitoring and only limited human interference (such as when there is need for use of lethal weapons), there could be one operator to monitor numerous USC's, further reducing cost per ship.

In addition to manning, the cost of the hull and outfitting will be less because of the deletion of offices, berthing, galley, recreation and other human services. Some of the machinery and piping such as potable water, Vacuum, Collection, Holding and Transfer (VCHT) systems, Collective Protection System (CPS) can potentially be eliminated. Berthing and office deletions include ventilation, air conditioning as well as lighting and LAN connections for personal computers. Equipment such as hot water heaters, self-contained breathing apparatus (SCBA) compressors, refrigeration, decontamination stations, cargo elevators, kingposts, rescue boats, internal communications and announcing systems, manned consoles, displays and associated wiring would not need to be installed.

There should be some cost savings realized since crew training and onboard training is not required.

A project headed by Dr. Richard Bucknall at the University College of London, UCL estimated that manpower is about 40 per cent of the cost of operating ships and that building crew accommodations and machinery is 30 per cent of the new build cost for a ship (based on commercial ships) [the digital ship, 2004].

USC Additional Cost Considerations

The major additional costs for the USC will be in the development of the required additional automation, and software and hardware costs to automate launch and recovery of USV's and UUV's (if deemed appropriate), refueling stations and docking processes. An initial cost estimate can be developed by leveraging current designs of USV's as well as capitalizing on current programs, such as the use of smart valves, automated damage control systems, and Voyage Management systems.

Reliability issues will be a factor. Cost to monitor the ship from a remote station needs to be included, including manpower, facilities and equipment necessary. Redundancy, reliability, and ease of depot maintenance need to be part of the USC design in order for it to realize the necessary lifecycle manpower savings.

Cost for testing of the USC may be higher than those for a conventional surface combatant due to the need to instrument and monitor a ship not built for manning.

Most of the high costs of a USC will be in design and development of automation, and setup of operations and support for this new class of ship. Once design is proved out and problems corrected with the first couple of ships, follow ship costs should decrease. If a USC can take the place of a manned surface combatants, as more are built, the potential for savings increases.

F. RISK ASSESSMENT

As with any unproven concept there are many risks associated with the proposed USC concept. Risks were identified in the Design Phase, Acquisition Phase, and Operations Phase of the USC life cycle. To properly assess the USC concept the team identified the risks in each phase and assigned each one a risk level. The team used the figure below to assess the levels of different risks for a USC concept.

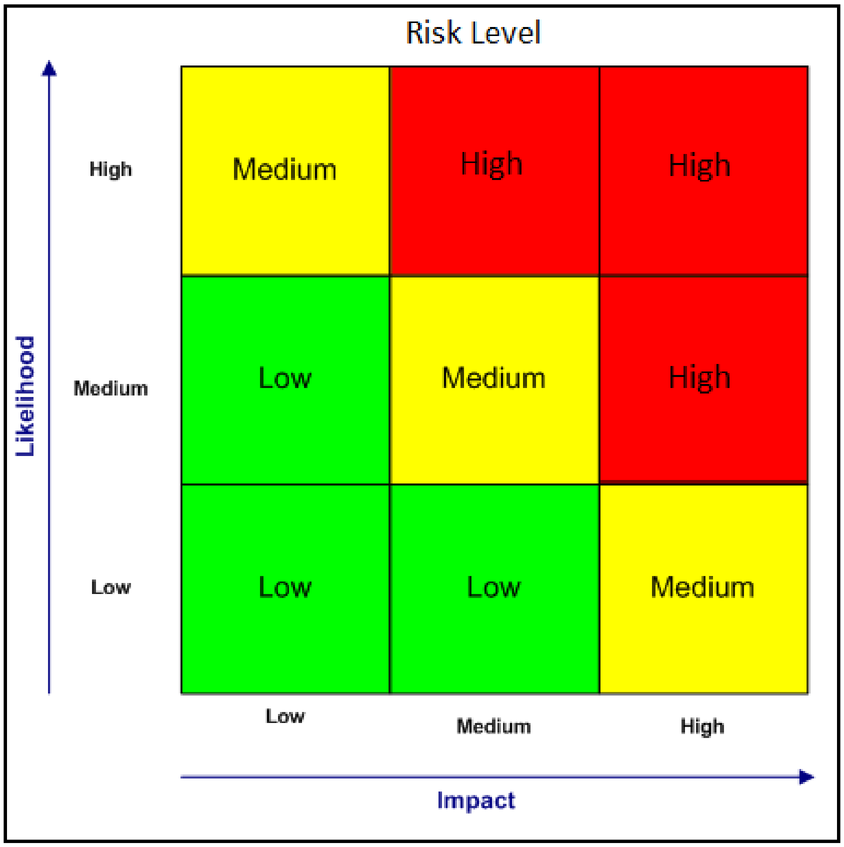

Figure 13. Risk Matrix

The two factors that influence the risk level are the likelihood that the risk will occur, and the consequence or impact of the risk if it does occur. For the USC concept in this report Low, Medium, and High rankings for each factor were determined to be acceptable. As the concept is further refined the risk list should be updated, and a larger number of discrete sections for each factor should be used.

Mitigation strategies were developed for all USC risks that were identified. The Medium and High level risks for each phase and the mitigation strategies are discussed below. The full risk assessment can be found in APPENDIX I – RISK ASSESSMENT.

Design Phase Risks

The Design Phase is comprised of the Research and Development associated with each individual technology as well as the USC concept design as a whole. The Design Phase had lower risk levels compared with other phases. While low technology maturity in this phase

might drive higher risk for the likelihood factor, there is lower impact of technical failure in this phase as compared to the impact of acquisition or operations failures, when a substitute technology is less likely to be available. As a result, no Design Phase risks had an overall High rating. The one Medium Design Phase risk was that the system components could not be modified for fully autonomous operation. The likelihood and impact of this risk are both Medium resulting in a risk level score of Medium.

The mitigation strategy for this risk was for alternative technology options to be investigated. Identifying more than one technology that can perform a function will not only allow for secondary options to be chosen, but could also help guide modification of the primary option to become autonomous. A second mitigation strategy is to track the constraining design features that do not allow for autonomous operation and to change these features to allow for the primary option to be used autonomously. By tracking the integration of the separate systems into the whole USC design, modifications to or swapping of different technology options becomes easier.

Acquisition Phase Risks

The Acquisition Phase is comprised of USC production and testing. This phase has many of the high risks for the USC because this phase is where the concept design is proven. An unproven concept will likely result in both appreciable cost and schedule delays. Therefore the likelihood of these risks is higher than other phases, and the impact is higher than in the Design Phase. There were four High level risks identified in this phase. The high level risks involved sub-system integration, component interoperation, C3 programming complexity, and C3 programming sufficiency.

The one mitigation strategy for all of these High level risks was to allow extended programming time, and additional and enhanced system and component testing. Time must be budgeted in the schedule for the extreme amount of programming necessary to allow the USC to function autonomously. Because of the autonomous nature of the USC concept, and the fact that this is a completely new design, the developmental and operational testing for the USC should be thorough. Testing of critical components and operations should be meticulous and have extremely high standards of success.

Additional time for programming and testing operations will also be needed because of the iterative nature of the two operations. If testing uncovers a deficiency in the USC programming, there must be sufficient time and resources to correct the programming and re-test. Fortunately, much of the USC programming can be tested by running simulations directly on the USC. The USC AI can be tested without having to perform live operational testing by simulating sensor data instead of actually collecting it. In order for these simulations to be effective, they will have to include realistic sensor data the USC would receive in live operational testing. Additionally, the simulations must be varied enough to cover the wide range of possible scenarios the USC could face.

Operational Phase Risks

The Operational Phase is when the USC is actually fielded and in service. Risks during this phase have a higher impact because the USC is in the operational environment instead of testing or design. There were four High and Medium level risks in this phase including: USC losing communication with command, USC being unable to process sensor data or processing sensor data incorrectly, USC incorrectly performing IFF and taking subsequent action, and USC not recovering from damage sufficiently.

Should the USC lose communication with Command (shore/ship), it can still function in a rogue state. The impact of this risk would be high. As a mitigation strategy for this risk, the USC could be programmed to "reset" or return to home base if communication from command is not received on some regular time interval. The communication from command would confirm the orders for the USC. If this communication were not received, then the USC would abort its current mission and reset and wait for further orders, or return to home base. This fail-safe mechanism would prevent the USC from performing an unwanted operation due to lack of communication with Command.

If the USC encounters some unanticipated condition or conflicting data that it cannot process or cannot process correctly while operating, the impact would be high. This risk is a continuation of the adequate programming and testing risks from the acquisition phase. If the same issue

occurs during actual operations the USC could be vulnerable or perform an incorrect action in response to the data. Ideally these items should be discovered and resolved in the previous phase. However, simulations are not 100% reliable and this situation could occur. A mitigation strategy for this risk during the Operational Phase is to program the system to recognize signs of erroneous or conflicting data, and default to some basic action for the USC. An example of this situation would be if the USC were performing mine sweeping and received conflicting data on a mine like object. Instead of neutralizing the object the USC might only note the location and continue on the sweep if the sensor data is conflicting.

The highest impact risk for the USC was the incorrect identification of friend or foe. If the friend is incorrectly identified as a foe, the USC could engage the friendly force and either the USC or the friendly unit could be damaged or destroyed. If a foe was incorrectly identified then the USC could be damaged or destroyed. The loss of a USC is less severe than the loss of human life; therefore the desired outcome in these scenarios is for the USC to be damaged or destroyed instead of an incorrect IFF contact. In order to mitigate IFF errors rigorous testing of the IFF system should be performed throughout the acquisition phase. Additionally, two separate systems for lethal weapons use could operate in parallel pulling information from common and unique sensors. If and only if the analysis from the two independent lethal weapons systems matched could the weapons be used.

The final risk of the Operational Phase was the risk that the USC does not recover sufficiently from damage or system failure. This risk has an aggregate medium level, but the impact could vary widely depending on the amount of damage taken or the exact system that fails. Additional testing is again a mitigation strategy that should be used. Testing the USC systems in different damage and failure configurations will demonstrate what level of damage or failure is fatal to the USC. If fatally damaged the USC should have a self-destruct sequence so that enemy forces are not able to use its technology if recovered.

G. SUMMARY

There are many items to consider when discussing an autonomous USC concept. Many of the relevant technologies require only software or programming changes; however several technologies would require mechanical adaptation to be used aboard an unmanned ship. The physical architecture considerations are based on the primary military missions of ASW and MIW. Design philosophy, maintenance, refueling, and system integration were considered as well. This section found that preliminary cost discussion shows potential for a large cost savings. Lastly, the risks associated with an autonomous USC were considered, and high level mitigation strategies were suggested. The next section contains the final analysis.

IV. CONCLUSIONS

As the US Navy fleet ages and several assets are retired, there is an opportunity to develop unique solutions for critical missions. An autonomous USC could provide significant cost savings in a declining budget environment while also taking US sailors out of harm's way. The NPS Capstone project team investigated the potential for employment of an autonomous USC by using a modified waterfall systems engineering process model to step through USC concept constraints and considerations.

First the team conducted a Needs Analysis. The state of the art for USVs demonstrates successful implementation of several technologies including autonomous navigation. A logical next step in the USV evolution is to scale up the implementation of unmanned vessels from small boats to ships. There are several potential benefits to an autonomous USC including cost savings, improved performance for current capabilities, and expanded capabilities and missions. The eleven current US Navy missions were reviewed and the team determined that ASW and MIW are logical primary missions for an initial USC concept. The mission areas of MIW and ASW lend themselves to unmanned operation – they are vital but have very limited use of lethal force, which is mostly in self defense. The largest concern with an autonomous concept is the use of lethal force with no human left accountable. MIW does not typically involve lethal force, and the majority of the ASW operations are ISR, not engagement. In addition, there are many MIW and ASW technologies which are close to full autonomy. MIW is dangerous to perform, while area monitoring for ASW requires a high level of vigilance that a computer system could handle better than a human counterpart. Lastly, both systems rely heavily on sensor readings and data analysis that, if programmed correctly, a computer could perform more effectively and efficiently than a human. A survey of interested parties confirmed the decision to investigate design considerations and constraints for these two mission areas.

Second, during Operational Analysis, top level system constraints and lower level operational constraints were developed. These constraints were used to guide the development of the Concept of Operations. Next, a Functional Analysis was performed where functions for a USC concept were developed based on operational activities from the CONOPS. These functions were

used to evaluate the lower level constraints, and operational scenarios were used to validate the results.

During the Concept Discussion, relevant technologies that met the concept constraints were researched for each functional area. Enabling technologies as well as technology gaps were identified, and constraints and considerations for the physical architecture, design and operations, and system integration were discussed.

The argument for pursing a USC concept must contain cost considerations as well as technical considerations. Creating an autonomous USC will not only eliminate the cost for personnel onboard the ship, but would eliminate the cost of the ship systems that involve humans such as habitability systems, mess, quarters, work stations, etc. This cost reduction must be balanced against the costs associated with automating the ship functions, hardware and software development, and increased system test and evaluation. Even with the additional research and development costs of pursuing an autonomous USC, there is potential for significant cost savings over the life cycle of a USC.

The last section of the Concept Discussion was the risk assessment. The project team developed considerations for risks in three phases of the lifecycle for a USC: Design Phase, Acquisition Phase, and Operational Phase. There are many technical risks to the successful operation of a USC. The highest impact risk for the USC was the incorrect identification of friend or foe (IFF). This risk is mitigated slightly by the mostly non-lethal missions areas of ASW and MIW selected for consideration in this report. Other mitigation techniques include rigorous testing of the IFF system throughout the acquisition phase. In fact, a longer than average and more rigorous test and evaluation period for a USC and USC sub-systems is a mitigation technique for many of the technical risks for a USC concept.

As a result of the project analyses, the team determined that a USC can be realized by 2020. Investments in software are required to get many relevant technology systems over the last hurdles, and in some cases, mechanical adaptation will also need to occur. Specific areas which

require increased development are: mine neutralization, damage mitigation, C3 ship control system, weapons control and electronic warfare.

Once these targeted investments have been made, significant savings associated with a USC as compared to a manned combatant over the life cycle of the ship are possible. Most increases in cost for a USC would be in the design and development phase. Once the design issues are resolved and appropriate technologies demonstrated, follow on USCs should decrease in cost. A USC will also leverage the personnel costs savings over its lifecycle. The cost considerations presented in this report justify further exploration of a USC as a solution for some of the Navy's more challenging missions.

An initial USC concept is an excellent first step into the transition to autonomous unmanned combatants. Appropriate missions for this initial USC have been chosen to leverage current semi-autonomous systems, and minimize the occaision to use lethal force. Promising baseline technologies have been selected and areas for further reasearch and development have been identified. Regardless of budget environment, a strong cost case has been made for the USC as compared to peer ships. The considerations and constraints discussed in this report can provide a basis for future work for a USC design.

V. RECOMMENDATIONS

The project team recommends the following areas for future study:

Future work should focus on the details of the ship configuration. Ship architectures and arrangements should be explored. Details beyond a notional general arrangement should be considered such as the configuration of the mission modules, the mechanical components for the mission systems, and the storage capacity for ammunition, fuel and other supplies. Component integration into the full ship system and interoperability between sub-systems is an area that will need to be carefully considered.

A more in depth analysis of the relevant technologies should be performed with the goal of acquiring cost and performance data to allow for a rigorous system trade-off analysis. In addition, investigation of required modifications to these technologies is needed to evaluate what development will enable a fully autonomous USC.

The Central Control Computing Center and the total software integration of the USC is the most crucial element of the USC. Much more in depth analysis must be done in this area as an autonomous ship of this size, with these capabilities, has not been successfully fielded yet. This further effort should focus on scaling up some similar technologies and modifying those technologies to enable autonomous operation. Component interoperation should also be investigated. In the USC concept, all systems are controlled through the 4C; however the physical interoperation of components should be addressed as well.

Additionally the communication between the USC system and other Navy systems needs further study. Translation between human communication and computer (electronic) communication will need to be established. Communications must focus on allowing humans at a command station to understand messages from the USC as well as communicate back to the USC in a way the USC can understand. As more unmanned ships and vehicles are developed, the communication paths between unmanned vehicles must be investigated as well.

In order to fully evaluate the USC concept, a quantified concept evaluation, an engagement analysis, and a cost validation must be done. A quantified evaluation and an engagement analysis will identify the weaknesses of the design, such as susceptibility to EMP attacks, and allow for redesign to address the deficiencies.

Lastly, further study should include a look at the larger scope of naval operations, and how the USC concept presented in this report would change how the US Navy operates. The study should focus on the unique capabilities of the USC concept and the projected global environment in 2020. The study should address how the unique USC capabilities will enable the Navy to evolve new tactics, perform new functions, and change operations to overcome current and future challenges.

APPENDIX A – CURRENT UNMANNED SURFACE VEHICLE CHARACTERISTICS

	Length	Speed (max)	Endurance	Range	Hull	Propulsion	Mission	Comms	Max Payload	TOW	Sensors	Payload	Source
Silver Marlin (Elbit, Israel)	10.6m	45 knots	24-48 hrs	500 nm	glass reinforced plastic	Twin diesels	ISR); force protection; ASU & MIW; search-and-rescue; port and waterway patrol; EW	2 LOS datalinks and 1 narrow band BLOS Ku-band satcom link.	2,500 kg		Raymarine nav radar, an El-Op CoMPASS EO/IR director, 360 panoramic video surveillance sys; AIS receiver	Elbit ORCA Overhead Remote Control Weapon System capable of receiving either a 12.7 mm or 7.62 mm machine gun. Accurate firing range claimed to be 800-1200m.	Silver Marlin', Jane's Unmanned Maritime Vehicles and Systems, 9 Mar 2011; Elbit Systems, Telefunken Racoms brochure, 2009
Protector (Rafael, Israel)	9m or 11m RIB	40 knots	24 hrs (11m version)			diesel engine; waterjet	ISR; MIW; ASW;	Non-line of sight comms; line of sight controls			radar; Electro-Optical Director (EOD); 360º panoramic camera	mini-Typhoon; microphone; loudspeakers	"Protector", Jane's Unmanned Maritime Vehicles and Systems 23 Nov 2010; Rafael brochure, 2008
Sea Star	11m	45 knots		300 nm		9m: 1 diesel, 1 waterjet 11m: 2 diesel engines; 2 waterjets	Homeland Security; EW; ISR		2,500 kg		EO/IR; Sonar	Non-lethal weapon; stabilized gun & fire control; Public address system; ESM/ECM ELINT/COMINT	Aeronautics Defense Systems Ltd brochure
MCM USV	40 ft		5.5 hrs (2.5hr sweep; 1 hr loiter; 2 hr transit)		alum	twin 540hp Cummins diesel engines; propellers	MCM			2,500 lbs tow force @25 knots in sea state 2	Radar Video Cameras GPS	Microphone; Signal Horn; Hailer; Magnetic Sweep Cable; MK 104 Acoustic Generator; electric winch; primary & backup computers	PEO LMW/ PMS 406 Presentation 17 Nov 2010
X-3 (Harbor Wing, US)	50 ft		60 days		trimaran; composite sail	hard wing airfoil sail and hydrofoils; photovoltaic solar cells; lithium ion batteries	long-range, long duration open ocean missions; ISR		1500 lbs				"Unmanned sailboat takes shape in maritime surveillance project," Sam LaGrone, Jane's Navy International, 23 Jun 2011 PEO LMW/ PMS 406 Presentation 17 Nov 2011
Sea Fox (Northwind Marine, US)	16 ft				alum	200-hp JP5 jet engine	Riverine ops				swimmer detection, radar, sonar, cameras	listen/talk capability	PEO LMW/ PMS 406 Presentation, 17 Nov 2011 "Sea Fox", Jane's Unmanned Maritime Vehicles and Systems, 21 Jun 2011
ASW USV	36ft					twin diesels, waterjets			5,000 lbs	1,600 lbs @20 knots	Low Frequency Bi-static Mid Frequency Mono Static	USV Towed Array System (UTAS) Multi-static Off-board Source (MSOBS) USV Dipping Sonar (UDS	PEO LMW/ PMS 406 Presentation 17 Nov 2011

Flexible Agile Sweeping Technology (FAST) (ATLAS Elektronik, UK; ITT Corp.)	10m					2 Yanmar engines, waterjets	MCM			towing demo'd on trials with another CSB as well as drogues; 6-12 knots		coils; clip-on wire sweeps; can tow one or two acoustic sources	"FAST" Jane's Unmanned Maritime Vehicles and Systems, 30 June 2011
Piranha (Zyvecs Technologies)	54 ft	45 knots	40 days	2,800 nm @25 knots	carbon fibre infused w/ carbon nanotubes	2 Yanmar engines, waterjets			15,000 lb		L-3 Wescam MX-10 electro-optical sensor turret		"Navy League: Piranha pioneers carbon nanotube technology"; Jane's Navy International, 15 Apr 2011
Inspector Mk2 (ECA, France)	8.2m	up to 20 or >30 kt depending on configuration	15 hrs at 20 knots (Inspector Mk1)		semi rigid hull inflatable.	turbo-diesel engine coupled to a Z drive (Inspector Mk1)	fleet training, ISR, hydrographic survey, MCM, homeland security, fire-fighting, maritime interdiction			bow dedicated keel can carry acoustic sensors. Aft deck can receive A-frame & winch for launch and recovery of towed systems (e.g.,AUVs or ROVs).	multibeam echosounder, swath bathymetric sonar, sub-bottom profiler or acoustic doppler current profiler forward looking sonar/side-scan sonar	loud speaker and directional microphone non-lethal weapons ECA K-ster mine destructor	"Inspector Mk2" Jane's Unmanned Maritime Vehicles and Systems, 27 Jun 2011 "Inspector Mk1" Jane's Unmanned Maritime Vehicles and Systems, 4 Mar 2011
Survey Autonomous Semi-Submersible (SASS) ASV 6000 (Autonomous Surface Vehicles, UK)	6m	12 kts	48 hrs @ 8 kts	400 nm		direct drive diesel; option for diesel electric		RF/Satcom	200 kg		multibeam and side-scan sonar, USBL, video cameras	payload winch, inspection ROV and cable system, loud hailer	"SASS" Jane's Unmanned Maritime Vehicles and Systems, 6 May 2011
SASS ASV 9000 (Autonomous Surface Vehicles, UK)	9m	14 kt		1500 nm @10 kt		primary diesel, secondary electrical system			300 kg	Specialist versions designed for deploying AUVs and for towing sweeps and arrays	above and below water surveillance systems and an ROV for inspection down to 200 m depth		"SASS" Jane's Unmanned Maritime Vehicles and Systems, 6 May 2011

USV 2600 (SeaRobotics Corp., US)	4m	4 m/s	4-40 hrs				autonomous survey; shallow water bathymetry; stream gauging; and hydrographic data acquisition. Can deploy SeaBotix LBV for hull and mine-like objects investigation.	RF Comms				single- or multi-beam echosounders, sub-bottom profilers and side-scan or imaging sonar. CTD, transmissometers, acoustic backscatter sensors, spectrometer, magnetometer, winch-deployed towfish, and an Acoustic Doppler Current Profiler (ADCP)	"USV-2600" Jane's Unmanned Maritime Vehicles and Systems, 9 May 2011
Venus USV (ST Electronics, Singapore)	9m	50 kt	8 hrs								V180 day camera from STELOP for day/night surveillance. Weapon of Mass Destruction Detector System.	DUBM 44 towed Synthetic Aperture Sonar for MCM missions; OTO Melara Hitrole remote weapon station for force protection missions; the Mini-T stabilised surveillance payload.	"Venus" Jane's Unmanned Maritime Vehicles and Systems, 7 Jul 2011
U-Ranger USV (Calzoni S.r.l., Italy)	7m & 11m	40 kt			Alum	stern drive props	ISR, coastal security, MIW, ASW, amphib warfare, UAV/UUV support, comms relay, naval target towing & hydrographic research				visible light/IR sensors surface sensors and effectors, a forward looking sonar (Reson SeaBat 7128)	microphone/loudspeaker Archimede harbour protection system. visible light/IR camera, pan-tilt zoomable camera, pan-tilt searchlighting, compass and inertial sensor, GPS receiver, marine radar with ARPA, forward looking sonar, sidescan sonar, Dyad sweeps and non-lethal anti-diver charges	"U-Ranger" Jane's Unmanned Maritime Vehicles and Systems, 28 Oct 2010

APPENDIX B – INTERESTED PARTY SURVEY

Unmanned Surface Combatant (USC)
Approach to Establishing Consensus Regarding Ship Mission Priorities

December 1, 2010

<u>Purpose</u>

Students enrolled in the Capstone Project course as part of the Systems Engineering Masters program at the Naval Postgraduate School were tasked to consider how a truly unmanned surface combatant (USC) can be defined and how the surface combatant missions can be satisfied without people.

As a first step, the team needs to choose mission areas to be performed by the USC – potential missions have been researched and a subset is described later in this document. Mission priorities need to be established in order to further investigate associated capabilities, and to develop system requirements. The team wishes to solicit and combine multiple stakeholder inputs via the included survey in order to choose top mission areas on which to focus.

<u>Project Background</u>

Operations and Support (O&S) costs are the largest portion of the Navy's total ownership costs for today's surface combatants. Surface combatants are designed and built to have a service life of 30 to 35 years, and manning costs are a major portion of the Navy's budget. Recent programs have reduced their manning requirements with mixed results.

Studies aimed at significantly reducing or eliminating manning have concluded that some degree of manning is necessary. This notion of required manning is rooted in years of culture; legal, ethical, and political reasons; and safety. As a result, studies with a true "out of the box" approach to achieving an unmanned surface combatant (USC) have not been attempted by the Navy.

Besides the elimination of high manning costs, achieving a design for a completely unmanned surface combatant offers other advantages including the elimination of many human interface features and habitability systems currently required on surface combatant designs. By eliminating these design features (i.e., operator consoles, berthing, lounges, mess rooms, offices,

medical spaces, galleys, etc) and their requisite space, weight and power allowances, the ship design trade space will achieve more flexibility and overall ship size may be reduced as well. Therefore, the objective of this project is to identify the enabling technologies that would allow for a USC to achieve full capabilities and be implemented for production and use. In addressing this problem the project group will first define the surface combatant design domain by identifying the capabilities associated with current and projected future missions. Secondly, the project team will attempt to quantify the constraints for development and use, and determine potential solutions. Thirdly, if a limited human presence aboard the USC is mandated due to concerns noted above, the project team will investigate the optimal way to include that presence as a space and weight reservation in the USC design. Lastly, the project team will attempt to quantify the reduction in total ownership costs for the USC vs. a manned surface combatant.

Survey Methodology

The Analytic Hierarchy Process (AHP) will be used to prioritize USC missions from the responses of a group of interested parties to a survey instrument. The AHP structures a decision problem as a hierarchy, or tree, starting from a goal at the top level and working downwards through progressive levels of criteria. Interested parties are asked to make pair-wise comparisons of two criteria at a time, and this information permits a ranking and weighting of all criteria to be synthesized using the AHP. The AHP permits participants to use all information available to them as they respond to the survey instrument, indicating the relative importance of one criterion over another. This process focuses thinking, and makes one criterion (or alternative) effectively the unit of measure for another. It accepts that stakeholder preferences and priorities may not be linear with quantifiable data and permits this to be expressed and considered in the process and prioritization. The AHP mechanics permit inconsistencies to be measured and pointed out for further discussion and corrected as needed by participants. The AHP also permits synthesizing preferences from multiple stake-holders, and may be used to help establish a consensus.

Missions

The team has identified the following Missions as potentially feasible for a USC to perform:

1. Anti-Air Warfare (AAW) - The destruction or neutralization of enemy air platforms and airborne weapons, whether launched from air, surface, subsurface, or land platforms.

2. Amphibious Warfare (AMW) - Attacks, launched from the sea by naval forces and by landing forces embarked in ships or craft, designed to achieve a landing on a hostile shore. This includes fire support of troops in contact with enemy forces through the use of close air support or shore bombardment.

3. Anti-surface Ship Warfare (ASU) - The destruction or neutralization of enemy surface combatants and merchant ships.

4. Anti-submarine Warfare (ASW) - The destruction or neutralization of enemy submarines.

5. Command, Control and Communications (CCC) - Providing communications and related facilities for coordination and control of external organizations or forces and control of unit's own facilities.

6. Electronic Warfare (ELW) - The effective use by friendly forces of the electromagnetic spectrum for detection and targeting while deterring, exploiting, reducing, or denying its use by the enemy.

7. Intelligence (INT) - The collection, processing, and evaluation of information to determine location, identification and capability of hostile forces through the employment of reconnaissance, surveillance, and other means.

8. Mine Warfare (MIW) - The use of mines for control/denial of sea or harbor areas, and mine countermeasures to destroy or neutralize enemy mines.

9. Mobility (MOB) - The ability of naval forces to move and to maintain themselves in all situations over, under, or upon the surface.

10. Naval Special Warfare (NSW) - Naval operations generally accepted as being unconventional--in many cases clandestine--in nature. NSW includes special mobile operations, unconventional warfare, coastal and river interdiction, beach and coastal reconnaissance and certain tactical intelligence operations.

11. Strike Warfare (STW) - The destruction or neutralization of enemy targets ashore through the use of conventional or nuclear weapons. This includes, but is not limited to, strategic

targets, building yards, and operating bases from which the enemy is capable of conducting air, surface, or subsurface operations against U.S. or allied forces.

Survey

The questions that follow refer to the missions described previously. A series of comparison questions are presented asking you to indicate whether one Mission is more or less important relative to another for the purpose of developing requirements for a USC. When responding to the questions, please consider the importance of performing each mission in an unmanned environment.

When performing your survey, please use the five point scale presented below.

Circle (or BOLD, or change text color of) the choice representing the alternative you consider to be more important. For example:

Which mission do you consider to be more important for the USC to support?

Mission 1 Mission 2

5 4 3 2 1 2 3 4 5

In the example above, Mission 2 is judged to be moderately more important than Mission 1.

INTENSITY	DEFINITION	EXPLANATION
1	Equal Importance	Two activities contribute equally to the objective
2	Moderate	Experience and judgment slightly favor one
3	Strong	Experience and judgment strongly favor one
4	Very Strong	An activity is favored very strongly over another
5	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation

Space is provided for you to briefly explain your rationale for the judgment provided and/or how you would use unmanned devices, if available, to perform the mission.

1) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Amphibious Warfare

5 4 3 2 1 2 3 4 5

2) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Anti-Surface Ship Warfare

5 4 3 2 1 2 3 4 5

3) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Anti-Submarine Warfare

5 4 3 2 1 2 3 4 5

4) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Command, Control, and Communications

5 4 3 2 1 2 3 4 5

5) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Electronic Warfare

5 4 3 2 1 2 3 4 5

6) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Intelligence

5 4 3 2 1 2 3 4 5

7) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Mine Warfare

5 4 3 2 1 2 3 4 5

8) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Mobility

5 4 3 2 1 2 3 4 5

9) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Naval Special Warfare

5 4 3 2 1 2 3 4 5

____
____
____
____
____

10) Which Mission do you consider to be more important for the USC to support, and how much more important?

Anti-Air Warfare Strike Warfare

5 4 3 2 1 2 3 4 5

____
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____
____
____

APPENDIX C – MIW TECHNOLOGIES

MINE WAREFARE CURRENT TECHNOLOGIES

Mine Hunting

AN/AQS-20A: The AQS-20, a system which has been in development for several years, is the follow-on to the AQS-14 (a detection and classification sonar). It provides full mine reconnaissance capability including detection, classification and identification by scanning the water in front and to the sides of the vehicle as well as the sea bottom for mines. The system uses sonar and electro-optical sensors to provide high-resolution images of mines and mine-like objects as well as high-precision location information [Anon, 2007].

Figure 14. AQS-20

The AQS-20 can either be towed from a MH-60S or from a Remote Minehunting Vehicle (RMV), so it has some further development required in order to be towed directly from the USC. The AQS-20 can be towed in both deep-ocean and littoral waters and it can detect, classify and localize bottom, close-tethered and volume mines.

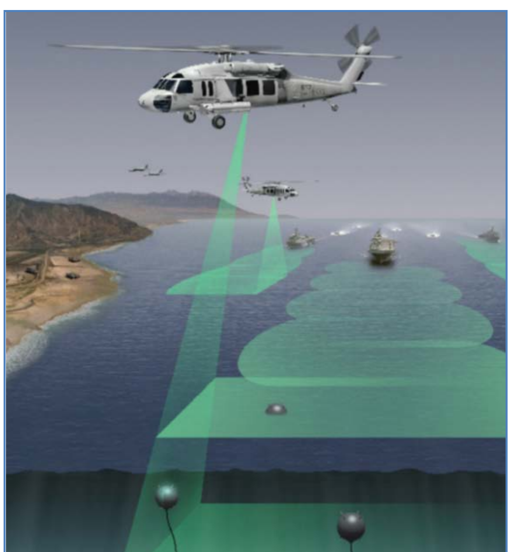


Figure 15. ALMDS

AN/AES-1 ALMDS: The Airborne Laser Mine Detection System (ALMDS) is another detection, classification and localization system which looks for floating and near-surface moored mines using pulsed laser light and streak tube receivers housed in an external equipment pod. ALMDS is capable of day or night operations, and the design uses the forward motion of the aircraft to generate image data [Anon,

2011].

Unlike the AQS-20, this system is fixed to the helicopter and not towed from the platform. Leveraging the height of the helicopter above the water to provide a broad swath view, the ALMDS is able to cover more surface area in a shorter period of time. However, this also means it will need to remain an airborne system so it will need to be deployed via an unmanned platform such as the VTUAV. Adding a UAV to the USC would add complexity, cost and weight, but also increase capability.

Mine Neutralization

AMNS: The Airborne Mine Neutralization System (AMNS) is a mine neutralization system which was originally deployed by ship and then adapted to the MH-60S. It consists of a SEAFOX vehicle which is deployed once a mine-like object has been identified. This vehicle is a self-propelled, unmanned, wire guided munition with homing capability that expends itself during the mine destruction process. The system is guided by a person and then detonated once the mine comes into view. According to Lockheed Martin, the developer, the AMNS has the following characteristics:

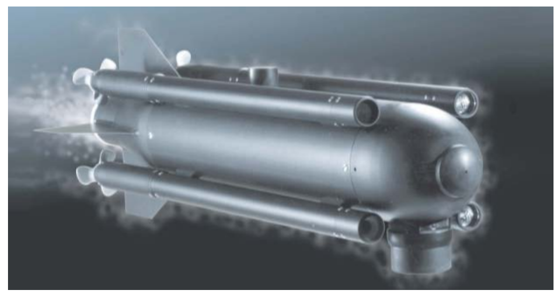


Figure 16. AMNS

• Certified warhead capable of destroying sea mines by detonation of mine explosives, including insensitive PBX.

• High degrees of operator-controlled maneuverability, including hovering, backing, and precise pitch and yaw control

• Vehicle tracking by host platform sonar activation of dorsal-mounted transponder.

• Acquisition, homing, and classification sonar system capable of horizontal mechanical scanning with a resolution down to 0.9 degrees.

• Control and guidance system, including attitude, heading, depth, and altitude sensors.

• Video camera and headlight for visual identification.

• High endurance battery power supply.

• Free spooling fiber-optic cable for high rate video, data transfer and control.

• Operator-selected method of warhead detonation [Anon, 2011].

Figure 17. Archerfish

Archerfish Mine Disposal System: The Archerfish has similar maneuvering characteristics to the AMNS and is also guided by wire to the point where it is detonated. The main difference between the Archerfish and the AMNS is that four Archerfish are contained in a pod and so the system can detonate four mines before another system has to be deployed. Also, the archerfish is designed to be deployed from the MH-60S so it will need more modification to deploy off of a USC, or need use of a VTUAV or other similar UAV[Anon, 2011].

Mine Sweeping

OASIS: The organic airborne and surface influence sweep (OASIS) system provides high-speed influence mine sweeping capability by generating and imparting underwater magnetic and acoustic signature fields capable of sweeping a wide range of magnetic, acoustic and combination magnetic/acoustic influence threat mines at tactically significant water depths. The towed body measures its height above the bottom using a transducer and its depth using a pressure sensor in order to provide guidance and control signals to the towed body control surfaces [Anon, 2011].

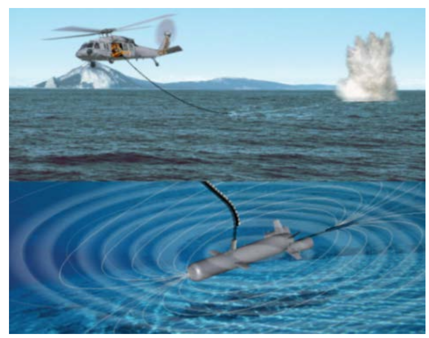


Figure 18. OASIS

Figure 19. UISS

UISS: In its current development, the Unmanned Influence Sweep System (UISS) consists of a suite of systems: a USV which tows the Unmanned Surface Sweep System (US3), radios/comms equipment [Multi-Vehicle Communication System, VRC-99 (Future RT/1499) Radio, Iridium Radio (Back-up), and Antennas], and host ship software (Multi-Operator Control Unit, Core System Controller, Payload Control Interfaces, Video, and Mission Planning) [Ashton, 2010]. Since the host ship in this case is already unmanned, this system could be reduced to just

the US3, which is an acoustic and magnetic influence sweep system using a MK104 towed acoustic device.

APPENDIX D – NAVIGATION TECHNOLOGIES

Elbit Systems

The Elbit Systems USV is designated for intelligence, surveillance and reconnaissance (ISR) missions, force protection/anti-terror missions, anti-surface and anti-mine warfare, search and rescue missions, port and waterway patrol as well as electronic warfare. The system is designed to optimize the performance of low-level control activities such as optimal turning rate, optimal speed for fuel consumption, and accurate sailing and navigation with cruise sensors and stabilization systems. Here is a list of the ANS Main Characteristics:

- Mission Range:
  - For Line of Sight (LOS) Communication: 60 km
  - Range at Wide Open throttle: 500 NM
- Vessel length: 10.6 m
- Vessel endurance: 24-36 hours
- Max. payload (payload vs. fuel trade-off) 2,000 kg
- Vessel overall weight: 6,500 kg
- Max. speed: 45 knots
- Propulsion: Propellers
- Engines: 2 x 315 HP (Diesel)
- Dual use: Manned-Unmanned Operation

Autonomous Navigation System

The AMN system is composed of various layers of perception, processing, and control. The AMN system uses a suite of sensors to perceive the environment of the vehicle that it is serving. AMN's initial sensors consist of RADAR, LIDAR, stereo optical cameras, GPS, AIS and a 360-degree camera. Fusion algorithms are used to compile and correlate these data into a common tactical picture for the USV. This picture is passed to a module for autonomous decision making, which in turn yields control outputs to the USV control systems.

APPENDIX E – ASW TECHNOLOGIES

U.S. Navy AN/SQQ-89(V) Anti-Submarine Warfare / Undersea Warfare Combat System (ASWCS / USWCS)

The current system for ASW, the U.S. Navy AN/SQQ-89(V) Anti-Submarine Warfare / Undersea Warfare Combat System (ASWCS / USWCS), used on CG and DDG class ships, and provides the technical foundation for the system planned for the LSC and DDG 1000, is shown in Figure 20. The AN/SQQ-89(V) provides an integrated ASW capability. “The system presents an integrated picture of the tactical situation by receiving, combining and processing active and passive sensor data from a hull-mounted array, towed array and sonobuoys. The AN/SQQ-89(V) consists of a hull-mounted sonar (SQS-53 series), wideband omni-directional receivers supporting acoustic intercept, Towed Array Sonar (AN/SQR-19 or Multi-Function Towed Array (MFTA)), and integrates with the Light Airborne Multi-Purpose System (LAMPS MK III and Block II Upgrade) helicopter for sonobuoy signal processing. The AN/SQQ-89(V) series is the first integrated surface ship (ASW) combat system. It has a continuing development program, as well as an open system architecture to provide for future capabilities.”

The AN/SQQ-89(V) ASW system is not autonomous but is highly integrated. In order to engage and launch weapons against a subsurface threat the AN/SQQ-89(V) interfaces with the Torpedo launch system, the Vertical Launch System (VLS), and the Aegis Weapon System (AWS).

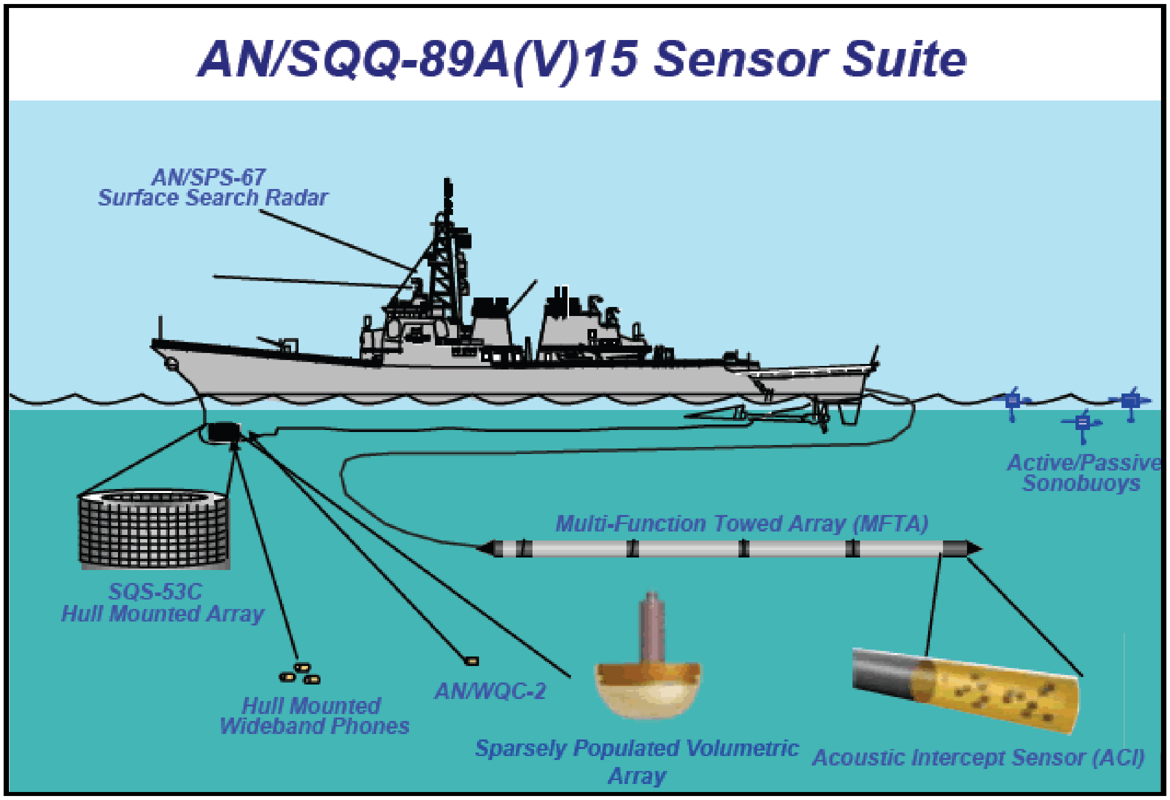


Figure 20. ASW Sensor Suite

The three types of sonobuoys are described below:

- Active sonobuoys emit sound energy into the water, receive the returning echo and transmit that information via UHF/VHF radio to a receiving ship or aircraft. Originally active sonobuoys pinged continuously after deployment for a predetermined period of time and then the device was scuttled. Later some sonobuoys, e.g., Command Activated Sonobuoy System (CASS) sonobuoys, allowed aircraft to trigger pings or scuttling via a radio link. This evolved into DICASS (Directional CASS) in which the return echo transmitted bearing as well as range data.
- Passive sonobuoys emit nothing into the water, waiting for mechanically generated sound waves from ships or submarines, or other acoustic signals of interest, to reach the hydrophone that are then transmitted via UHF/VHF radio back to a ship or aircraft.

- Special purpose sonobuoys relay various types of oceanographic data to a ship, aircraft, or satellite. There are three types of special-purpose sonobuoys in use today. These sonobuoys are not designed specifically for use in submarine detection or localization.
    - BT—The bathythermobuoy (BT) relay bathythermographic or salinity readings, or both, at various depths. This information is then utilized to process acoustic data since the propagation of sound waves is affected by both temperature and salinity.
    - SAR—The search and rescue (SAR) buoy is designed to operate as a floating RF beacon. As such, it is used to assist in marking the location of an aircraft crash site, a sunken ship, or survivors at sea.
    - ATAC/DLC—Air transportable communication (ATAC) and down-link communication (DLC) buoys, are intended for use as a means of communication between an aircraft and a submarine, or between a ship and a submarine.

The three lightweight torpedoes considered for USC use are listed below.

US Mk 54

The Mk 54 Lightweight Hybrid Torpedo (LHT) offers shallow water capability for surface launches in water as shallow as 25m and air launches in 35m. The LHT is a hybrid design with the warhead, fuel tank and afterbody of the Mk 46, sonar and thermal battery of the Mk 50, signal processing and speed control valve of the Mk 48 Mod6, and software components from both the Mk 50 and Mk 48 ADCAP.

Franco-Italian MU90 IMPACT

The Franco-Italian MU90 IMPACT was developed from scratch with littoral threats in mind. It can be launched in depths limited to just 20m (shipborne) or 25m (airborne). The MU90 offers variable speeds from 29 to over 50 knots with continuous adjustment available and corresponding ranges from 25,000m to 15,000m. With its insensitive munition warhead, broadband sonar processing and tactical computer, high immunity to acoustic countermeasures, propulsion quietness and lack of wake, the MU90 provides today the performance envisaged for

the future Mk54 P3I. MU90 users included France, Italy, Germany, Poland, Denmark and Australia, with two South American and South-East Asian countries likely to follow soon.

UK Sting Ray

The Mod 1 Sting Ray is believed to have a maximum speed of about 45 kt with an estimated endurance of some 8 minutes at that speed. Maximum operating depth is believed to be about 1 km. The Sting Ray has been exported to Egypt, Norway and Thailand.

APPENDIX F – SELF DEFENSE TECHNOLOGIES

SELF DEFENSE CURRENT TECHNOLOGIES

ARGC-2400

A long range camera (ARGC-2400) is available from Canada which offers long range imagery in complete darkness and adverse weather, and records them with the appropriate parameters. The camera uses range-gating technology with the DALIS (Diode Array Laser Illumination System), slaved to the field-of-view of a color CCD camera (with a FoV ranging from 2° to 45°) with a motorized continuous zoom, offering magnification up to ×240. The camera can rotate 360° and has a radar interface allowing faster pointing to targets of interest. This camera also has internal sensors to remotely monitor camera status. Camera visual record can be transmitted back to controlling unit for ID of hostiles and intent of suspect craft.

Figure 21. ARGC-2400 long-range night-vision camera [Anon, 2011]

Video Image Retrieval and Analysis Tool (VIRAT)

VIRAT is a DARPA project which relies on video matching. The system can be shown a video clip of interest (in this case perhaps images of known pirate ships or pirates with guns), and it will look for similar video in the ISR imagery. It can also match a behavior of interest, given an example of the same [Peck, 2010]. This software is still in the early development phase and is not currently focused on marine uses.

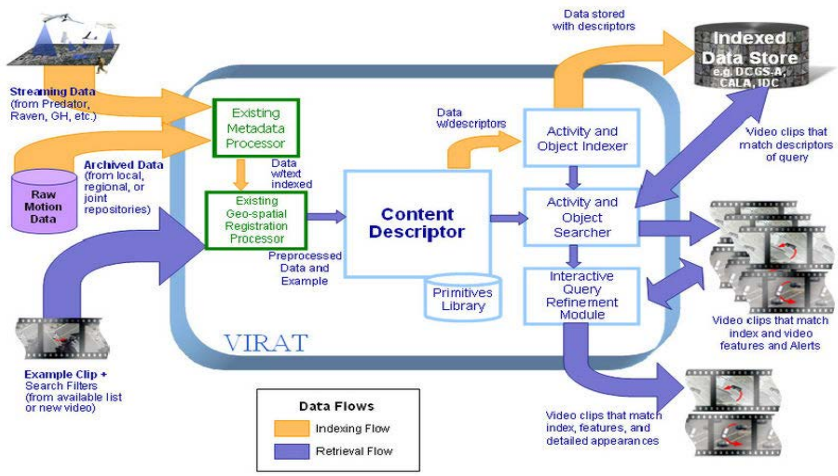


Figure 22. VIRAT Concept Diagram [Anon, 2011]

LONG RANGE ACOUSTIC DEVICE (LRAD)

Figure 23. LRAD 1000Xi™ Long Range Acoustic Device [Anon, 2011]

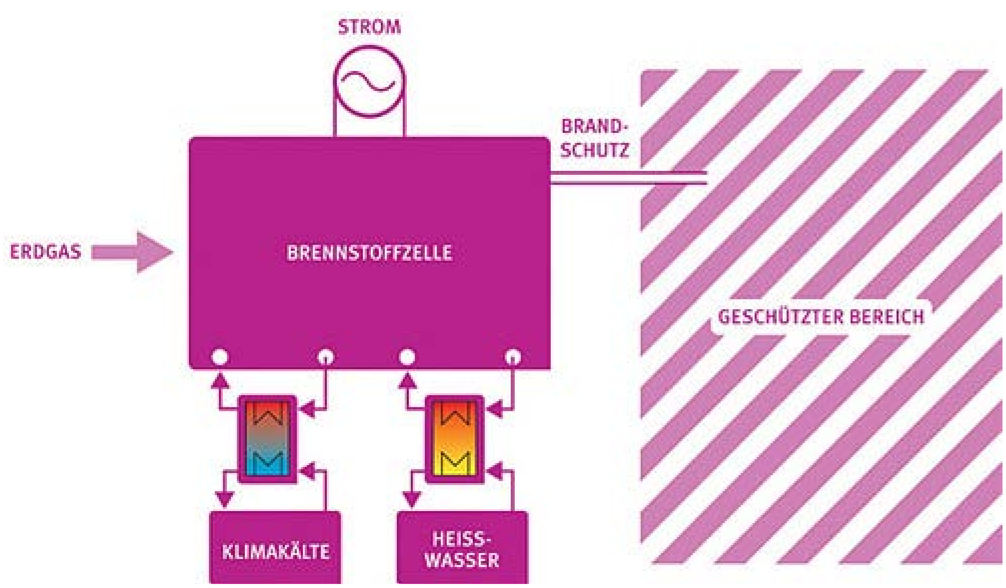
APPENDIX G – DAMAGE CONTROL TECHNOLOGIES

DAMAGE CONTROL TECHNOLOGY

N2telligence
http://www.n2telligence.com/

Electric power 100 kW
Voltage 400 VAC
Frequency 50 Hz
Heat recovery ~ 50 kW at 55 ° C
~ 50 kW at 90 ° C [1]
Energy efficiency ~ 82%
Fire Protection 50 m^3 room size up to several 1,000 m^3
Energy Natural gas / biogas
Operating mode Fully automatic, network operation
Dimensions 2.2 m (W) x 5.6m (L) x 3.4m (H)
Weight 15.5 t in operation

Simple principle - complex effect.
quattro generation in detail.



Natural gas comes in, fire comes out.
You also get heat, air conditioning and electricity

HUAV & EOD(HULS)
http://www.ocean-news.com/newsletter/799-onrs-autonomous-underwater-hull-inspection-vehicle-nearing-procurement

HUAV

An Office of Naval Research (ONR) autonomous underwater vehicle, which can maneuver under ships to detect explosives, is closer to reality following the awarding of a production contract in March.

Since that award, ONR researchers have been preparing for a demonstration of the Explosive Ordnance Disposal Hull Unmanned Underwater Vehicle Localization System (EOD HULS) in June at Naval Surface Warfare Center Panama City, Fla.

That test will be the last with the full system, said Dr. Thomas Swean an ONR research scientist.

"This will be a big demonstration of our capabilities. The system will go into the water to survey a ship," he said. "ONR developed an unmanned underwater vehicle (UUV) that could maneuver in very tight and complex areas."

On March 2, Massachusetts-based Bluefin Robotics was awarded a $30 million contract to produce EOD HULS. The goal is to develop a small and affordable autonomous vehicle that can inspect ships for anomalies.

Previously, teams of divers had been required to carry out inspections of hulls. That work often took hours to complete on vessels that could be as large as container ships, Swean said.

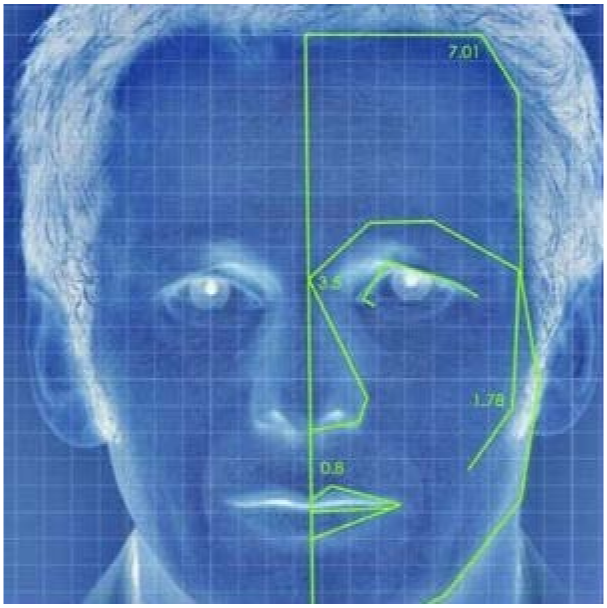
HULS evolved from the Hovering Autonomous Underwater Vehicle, an ONR initiative awarded to Bluefin and the Massachusetts Institute of Technology (MIT) in 2002. Bluefin designed the vehicle while MIT developed the control systems.

The EOD program office then turned the idea into the EOD HULS program with initial funding that started in 2006.

Three bids were received for the initial development phase, and the Bluefin team was selected. Under phase two, Bluefin developed prototype systems. Those UUVs passed all testing, leading to the March contract award for procurement of EOD HULS.

Besides the platform itself, ONR is also involved in developing many of the sensors being used on EOD HULS, Swean said. "Some date from as far back as the early 1990s."

Facial Recognition Technology



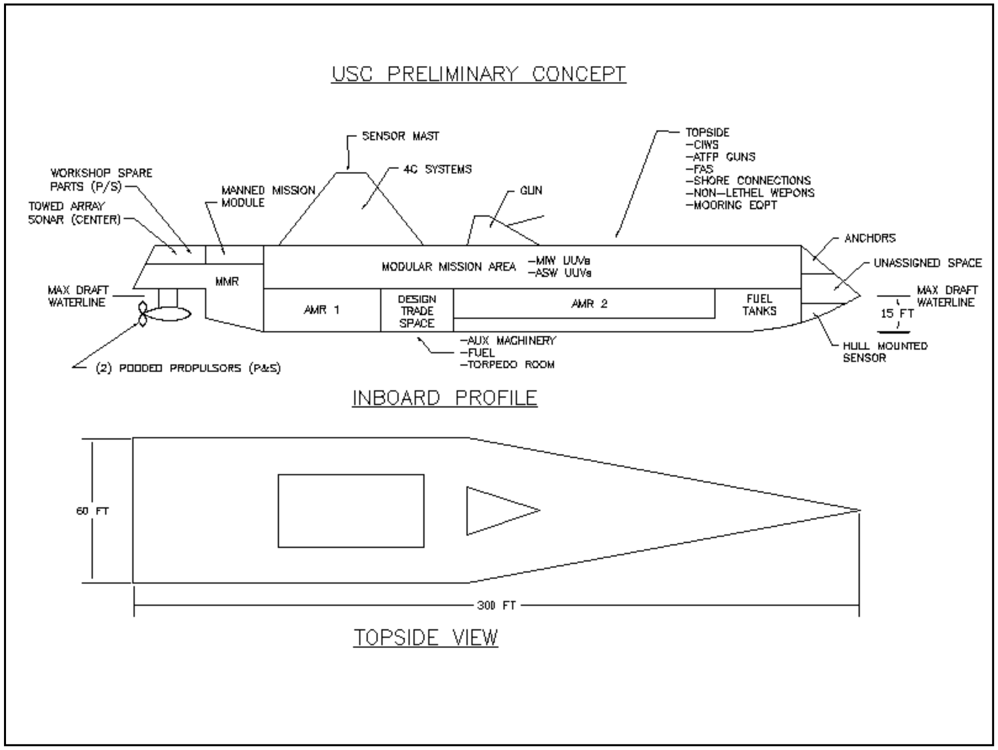
http://www.technobombs.com/comparison-between-2d-3d-facial-recognition-techniques-system/

“Because the face recognition system is used to distinguish faces according to the color, intensity or other facial features, the 2D seems to be functioning more appropriately to provide the required information. The conflict can be seen in the 3D recognition system that discriminates only the shape of the features. Despite being deemed to be more reliable and accurate, much improvement is still needed to apply the 3D system in real.”
http://technology.ezinemark.com/compare-2d-to-3d-face-recognition-system-17204e7f144.html

APPENDIX H – NOTIONAL USC CONCEPT BASED ON CONSTRAINTS

A. TOP LEVEL PHYSICAL ARCHITECTURE

Hull form – Monhull	**Length –** 300 ft	**Energy Conversion –** Fuel Cell
Hull Material – Glass Reinforced Plastic	**Beam –** 6o ft	**Propulsor –** Podded Propulors
	Draft – 15 ft	



B. TECHNOLOGY DECISIONS

In the main body of the report, technology gaps for fulfilling all of the USC functional areas were discussed. As a further step towards advancing the idea of a USC, suitable technologies have been selected for a notional USC concept based on non-rigorous, but rational comparative assessments. Most, if not all, of these technologies require further work in software and hardware development in order to integrate and provide full autonomy. The selections for each functional area are discussed below, and the rough level of work required to provide full autonomy is discussed in Section C of this appendix. Again, the purpose of this notional concept is not to provide a rigorous design of a specific USC for explicit requirements, rather it is to provide a possible USC concept that can enable further discussion and exploration of the USC idea.

1) **USC Central Control Architecture**

Technologies for Central Control Computing Center

The Total Ship Computing Environment (TSCE) under development for the DDG 1000 is a promising option which can provide the basis for the USC 4C. The TSCE is "an advanced, open systems architecture that provides a scalable platform for cost-efficient delivery of new mission capability while capitalizing on the reuse of millions of lines of code from existing Navy programs. The system delivers an unprecedented level of Mission Systems Integration and automation. As such, it is a primary driver for the 60 percent reduction in manning for the Zumwalt-class destroyer versus the requirement for today's Arleigh Burke-class destroyers" [Anon, 2006:1]. Development of the 4C will be based on zero manning and therefore will require a great deal of programming, system automation development, and artificial intelligence on a level that has not yet been accomplished.

The Command and Control function of the USC will be an integral part of the 4C. The Global Command and Control System, Maritime (GCCS-M), "provides maritime commanders at all echelons with a single, integrated, and scalable Command and Control system. GCCS-M fuses, correlates, filters, maintains, and displays location and attribute information on friendly, hostile, and neutral land, sea, and air forces. GCCS-M also integrates this data with available intelligence and environmental information to support command decisions [SPAWAR, 2011:1]."

This system is currently designed for a man in the loop implementation so it will require significant modifications to enable it to be used on the USC.

Technologies for Ship Control

This system is composed of 4 major sub functions that perform a wide variety of tasks. These tasks include Bridge and Navigation Control, Damage Control, Internal Ship Sensing, and Machinery Plant control. All of these control functions will require significant modifications and additions to existing systems to make them function on the USC.

Technologies for External Communication Control

The technologies that are currently used for combatants will be used on the USC but significant automation will be necessary to enable the communication systems to receive and transmit automatically. This will be a subset of the 4C system development. To accomplish external communications, the USC will require systems that allow communication with assets that are nearby (line of sight) and over the horizon. Over the horizon includes satellite capability so command authority can provide tasking / situational awareness information and allow the USC to provide information from any onboard sensor to other networked assets as well as organizations that provide monitoring functions. To accomplish the external communication control, the USC will require similar systems that are on other combatants. These include the following:

- VHF Line of Sight (LOS) - Navigation, USC Control Link,
- UHF Line of Sight - USC Remote Control
- Ku-band - Data distribution (including fire control, imagery, tactical control net) on the OPAREA level of ship location
- Ku-band SATCOM - High data rate (transmit and receive for real time communication
- L-band Line of Sight - Tactical Communication with joint forces (includes own service)
- L-band SATCOM - Navigation - GPS
- S-band - Data transmission, including imagery, video. Interoperable with DHS to support close in US coastal defense and emergency relief (need to check is this is listed as a USC mission)

- Electro Optical Line of Sight - Precision Launch and Recovery of UUV an UAV

Technologies to accomplish External Sensor Control (ISR)

The above-water sensor may consist of an EW suite similar to the ‘AN/SLQ-32 ECM (Electronic Countermeasures) system which uses radar warning receivers, and in some cases active jamming, as the part of ship’s self defense system. The SLQ-32 provides warning of incoming attacks, and is integrated with the ship’s defenses to trigger Rapid Blooming Offboard Chaff (RBOC) and other decoys, which can fire either semi-automatically or on manual direction from a ship’s ECM operators’ [Anon, 2011].

Technologies to accomplish Weapons Control

The USC will be armed with a variety of offensive and defensive weapons. The software to analyze sensor data and determine friend or foe, when the use of weapons is warranted, and which weapon is ideal for each situation, will reside in C2. Some of the intelligence data may be provided by the weapon systems themselves; however, decisions will be made within C2 as to when to fire the weapon or when to put the weapon on auto mode.

2) **Anti-Submarine Warfare**

Anti-Submarine Warfare trade-offs were made based on maturity, autonomy, and performance. ASW specific performance characteristics included:

- COTS – properly executed this implies rapid delivery of increased capabilities and performance to the fleet
- Signal Processing – this is key to much of the ASW problem. Future ASW capability will likely be found in new algorithms that provide more actionable information in the data currently provided. Also, the capability of sensors, the amount of data, and the number of devices provided will increase, requiring increased bandwidth, greater processing speed and more computing power.
- Interoperability – how likely these systems will be able to operate with existing systems

Table 14. ASW Package Decision Table

ASW Equipment	Maturity (1)		Autonomy (3)		Performance (2)							Total Score
					COTS (1)		SignalProcessing (2)		Interoperability (3)		Perf	
	score	total	score	total	score	total	score	total	score	total	Total	
Integrated Anti-Submarine Warfare / Undersea Warfare Combat System (ASWCS/UWCS)												
AN/SQQ-89	3	3	2	6	2	2	2	4	2	6	8	17
Integrated Sonar Suite	3	3	2	6	3	3	3	6	3	9	12	21

Decision Table Results

Only two systems were considered because no other deployed systems had the high level of interoperability required. Each system is detailed in APPENDIX E **– ASW TECHNOLOGIES**. The selected system, Integrated Sonar Suite, is highlighted in green above. This system was selected because it shows the most promise for further development and implementation on a USC, but there are still areas that have to improve in order for this system to work on a USC. Reasons why this system was preferred over the AN/SQQ-89(V) and specific shortfalls which still exist are discussed below:

Hull Mounted Sonar

The AN/SQQ-89(V) HMS was designed for deep ocean use and is too large and heavy to meet USC constraints. The nominal Ultra Integrated Sonar Suite (Ultra – ISS) provides a smaller dual frequency sonar that performs ASW, mine avoidance and object avoidance capability. The dual frequencies allow the HMS to be used for both ASW and mine hunting in deep ocean and the littorals. Despite a high degree of automation the Ultra ISS will still need to be fully automated and interfaced with the other sonar, navigation, weapons, and ship control systems.

Towed Array

The AN/SQQ-89(V) towed array requires a large handling system that is prone to maintenance issues and can sometimes damage the array. The Ultra – ISS provides linear towed array and VDS functionality in a single towed array. The VDS is not a “hard body” design so it does not require a large handling system. The array requires only two men to fully deploy and recover in a Sea State 6 and involves a single winch. This system uses less manpower and less complicated machinery and therefore would be much easier to fully automate than a standard VDS handling system.

Sonobuoys

Both systems are compatible with sonobuoys. Ultra is a sonobuoy manufacturer. Sonobuoys are currently either launched or dropped by hand over the side on surface ships. A USC would either need to have an automatic launcher or a simple mechanism to allow the sonobuoys to drop over the side of the ship.

ASW weapons

Both systems are compatible with ASW weapons systems. The AN/SQQ-89(V) has external interfaces to the MK 331 Torpedo Setting Panel (TSP), MK 41 Vertical Launch System (VLS), and the AEGIS Weapon System (AWS). Ultra – ISS processes data across all sensors so the system is able to execute both bi-static and multi-static processing between the HMS and VDS not only on a single vessel, but also between vessels, creating a Force ASW capability. This capability should allow for quicker transition from detect to engage.

There are three categories of weapons available for surface combatants to use against submarines: projectiles, torpedoes and missiles. Projectiles refer to bullets and similar armament and imply no "smart" capabilities. These devices are largely ineffective against a submarine. Torpedoes are the weapon of choice against submarines because they are effective and compared to missiles relatively cheap. Missiles can be used to rapidly deliver torpedoes closer to a target. To do so, however, requires the addition of both the required missile infrastructure, such as missile control panels, launch containers and resulting increased cost.

Three lightweight torpedoes were considered for USC use. All three are currently in production. Based on the limited data available and the desire for extremely high reliability, the US Mk 54 torpedo was selected - it is a hybrid design that uses parts from several earlier torpedoes. The Franco-Italian MU90 IMPACT would be a close second choice - it was developed from scratch for littoral use, has very long range, and can vary its speed to exceed 50 knots. Pending the availability of more information, especially reliability data, the MU90 IMPACT could become the preferred choice.

Design Table Results

The selected weapon is highlighted in green below. This weapon was selected because it currently shows the most promise on a USC, but there are still areas to investigate. The range information was classified and unavailable but the unclassified ranges are adequate for all littoral and most deep ocean use. Specific decision table results are listed below:

Table 15. ASW Weapon Decision Table

ASW Weapons	Maturity (1)		Autonomy (3)		Performance (2)							Total Score
					Range (1)		Versatility (2)		Effectiveness (3)		Perf Total	
	score	total	score	total	score	total	score	total	score	total		
Lightweight Torpedoes												
UK Stingray	3	3	2	6	1	1	1	2	1	3	4	13
MK54	3	3	2	6	2	2	2	4	2	6	8	17
MU90/IMPACT	3	3	2	6	3	3	3	6	3	9	12	21

3) **Mine Warfare**

In addition to maturity and autonomy, several mine hunting specific characteristics were used to judge relative performance. These included:

- System weight, including the means of deployment, i.e., a UAV if required
- Mechanism to deploy – this is the current deployment mechanism which will need to be altered when deployed from a USC. The weighting factors indicate perceived ease of shifting from the current method to a fully autonomous method
- Mission time – how long it will take to complete the mission with one of these systems
- Safety, i.e., safety to any people who might be involved in that operation today, and
- Capability, or ability to complete the task successfully.

Table 16. Mine Warfare Decision Table

Mine Warfare Assessment																
Sub-Functions and Systems	Maturity (1)		Autonomy (3)		Performance (2)											Total Score
					Weight (1)		Mechanism to Deploy (2)		Mission Time (3)		Safety (3)		Capability (4)			
	score	total	score	total	score	total	score	total	score	total	score	total	score	total	Perf Total	
Detect, Classify, Identify System																
Human	3	3	1	3	3	3	USC (3)	6	1	3	1	3	2	8	6	12
AQS-20	2	2	3	9	2	2	RMS/MH-60 (2)	4	2	6	3	9	2	8	8.4	19.4
ALMDS	2	2	3	9	1	2	MH-60 (1)	2	3	9	3	9	3	12	8.8	19.8
Engage (Neutralize) System																
Human	3	3	1	3	3	3	USC (3)	6	1	3	1	3	1	4	6	12
AMNS	2	2	2	6	2	2	MH-60 (1)/USC	4	2	6	3	9	2	8	8.4	16.4
Archerfish	2	2	2	6	2	2	MH-60 (1)	2	3	9	3	9	3	12	8.8	16.8
Engage (Sweep) Sytem																
Human	3	3	1	3	3	3	USC (3)	6	1	3	1	3	1	4	6	12
OASIS	2	2	3	9	2	2	MH-60 (1)	2	3	9	3	9	2	8	8.8	19.8
UISS	2	2	3	9	2	2	USV (2)	4	3	9	3	9	2	8	9.6	20.6

Decision Table Results

Current systems are highlighted in green above. Though these systems have been selected because they show the most promise for further development and implementation on a USC, there are still many areas that have to improve in order for these systems to work. Specific shortfalls are listed below:

Airborne Laser Mine Detection System (ALMDS) – The ALMDS is a high performance system, and while time required to complete the mission is significantly better than the AN/AQS-20 because its swath is wider, it will need to be mounted to an airborne vehicle such as the VTUAV which will increase weight, cost, and complexity. In addition, it suffers from the general autonomy deficiencies described in section III.A.c) – Mine Warfare.

Archerfish – Four Archerfish are carried in a pod which means that less launch and recoveries of the system are required to complete the mission. However, it will need to be adapted to launch and deploy from a USC, and it needs autonomy in place of the human guidance system to targets.

Unmanned Surface Sweep System (US3) – The US3 system is already deployed from a USV so deployment from the USC should not be much of an issue. The fact that a sweeping system is still used so often in missions is a testament to the mine warfare challenge. In a future with advanced autonomy and better identification of mines amongst bottom clutter, perhaps the mine sweeping role will be further reduced.

4) **Navigation**

The following technologies were considered as candidates upon which more research and development could lead to full autonomy for use onboard a USC. The performance criteria on which they were evaluated are listed below:

- Portability, since no autonomous system currently exists this was based on the perceived ease with which the technology demonstrated can be ported to another vessel.
- Collision avoidance was evaluated based on the robustness of the programming and demonstrated real world effectiveness.
- Data fusion was an assessment of the capability of the technology to integrate the various pieces, and demonstrate a rapid and efficient method of processing the data generated, then transforming it into a navigation response.

Table 17. Navigation Decision Table

ASW Weapons	Maturity (1)		Autonomy (3)		Performance (2)							Total Score
					Portability (1)		Collision Avoidance (2)		Data Fusion (3)		Perf Total	
	score	total	score	total	score	total	score	total	score	total		
Raytheon	1	1	1	3	2	2	3	6	2	6	9.33	13.33
Kongberg Maritime	1	1	1	3	2	2	3	6	2	6	9.33	13.33
Sperry Marine	1	1	1	3	2	2	3	6	2	6	9.33	13.33
Elbit Systems	3	3	3	9	2	2	3	6	2	6	9.33	21.33
Autonomous Maritime Navigation (AMN)	3	3	3	9	3	3	3	6	3	9	12	24

Decision Table Results

The performance characteristics specific to Navigation included portability, collision avoidance, and data fusion and are shown in Table 18.

Five separate manufacturers of navigation technology were considered.. Three integrated Bridge and Navigation manufacturers: Kongsberg, Sperry Marine, and Raytheon, were considered. A fourth manufacturer, Elbit Systems, a company that designs and builds UAVs and Unmanned Ground Vehicles (UGV), was also considered. The final manufacturer, a consortium of companies led by Spatial Integrated Systems (SIS), Jet Propulsion Lab (JPL), and Naval Surface Warfare Center Carderock Division (NSWCCD) has designed a portable, Autonomous Maritime Navigation (AMN) system to provide autonomy independent of platform.

Portability: Only one of the five systems, AMN was designed from the start to be portable to other ships. Each of the others was designed specifically for the ship on which it was installed

and in the case of the three Integrated Bridge and Navigation systems the objective was to reduce the number of operators, not to eliminate them altogether.

Collision avoidance: All five systems (ANS, AMN, Kongsberg, Sperry Marine and Raytheon) have demonstrated collision avoidance as a fundamental component of the navigation systems.

Data Fusion: Only AMN was designed from the start to operate exclusively autonomously by leveraging a sophisticated control system design used by the Mars Rover and implementing open system architecture to ease the process of adding additional capabilities and sensors.

AMN was chosen as the best base technology to build from. SIS, JPL, NSWCCD, and others developed the AMN program. AMN combines advanced 3D imaging technology, LIDAR, RADAR, multi-sensory data fusion, multi-dimensional processing algorithms, and state-of-the-art NASA Mars Rover artificial intelligence into an advanced sensor suite that is platform independent. The AMN design demonstrates a high degree of autonomy, while being tested at sustained speeds up to 30 knots and under severe weather conditions. AMN has demonstrated the ability to consistently detect and avoid buoys, channel markers, and range markers, at speeds up to 25 knots. The AMN is shown in Figure 24.

Figure 24. AMN

However, there is still more work to be done. AMN has demonstrated a novel autonomous product but not on a vessel of the size and complexity of a USC and scaling up the technology to

a corvette/frigate sized vessel will present many challenges. In fairness to all the other manufacturers, except SIS, full autonomy was not their objective so they may be capable of a formidable product if given the opportunity.

5) **Self Defense**

Detect to Engage – Combat Systems Software

There are various software packages available for the integration and central management of sensors and weapons. Combat Management Systems (CMS) main functions include surveillance and picture compilation for situational awareness using the on-board sensors and tactical data links, evaluation of threats, and automatic sensor and weapon assignment and kill assessment. Some CMS available for consideration are Terma's C-Flex, Thales's Tacticos, and Saab's 9LV. Other systems such as Raytheon's Ship Self-Defense System (SSDS) and Lockheed Martin's COMBATSS-21 are not considered at this time due to current known reliability problems (on LPD-17 and LCS-1 respectively), but may be considered at a later date when problems have been corrected.

Terma's C-Flex

C-Flex is currently used on various Royal Danish Navy classes of ships and on the Romanian Navy Marasesti Frigate. The C-Flex system is configured around a fiber-optic 1000/100 Mbit Ethernet LAN and is based on the T-Core Common Operational Environment. The system consists of COTS-units with Uninterrupted Power Supply (UPS) protection. Sub-System Interface Units (SSIU) replace the standard interface units with containerized weapons and peripheral sensors and perform the necessary conversion and adaptation of data formats and transmission protocols between subsystems and the C-Flex. This allows for subsystems to function independently in the event of damage or malfunction. Radar and video information is digitized at the sensor and transported on a parallel, separate TCP/IP network. Routing is carried out by the system if a degradation of the system occurs. Functionality includes picture compilation with unlimited tracks (up to 1,000 tracks with no performance reduction), AAW Threat Evaluation and Weapon Assignment (TEWA) - hard and soft kill, Link 11, Link 16 and 22, management of CIWS, mine laying functionality and helicopter control.[Anon, 2010]

Thales's Tacticos

Tacticos is used by 15 Navy's worldwide on more than 150 vessels, including on LCS-2 as ICMS. The system is comprised of command and control, command support and fire-control facilities for anti-air, surface, anti-submarine and electronic warfare as well as naval gunfire support. TACTICOS is based on a distributed computer architecture, applying a multinode, multiprocessor concept for battle damage-resistant configuration. Software is written in Ada and C++, and includes the SPLICE distributed database and data communication software that operates alongside a real-time version of UNIX. The console hardware is based on unmodified commercial off-the-shelf workstations, and hardware is linked through a redundant Local Area Network (LAN) formed by Ethernet, Fast Ethernet or ATM. There is a compact version of this system with limited functionality. [Anon, 2011]

Saab's 9LV

The 9LV is installed in numerous ships around the globe (114 systems delivered) and comes in different variants (Mk1, Mk2/2.5, Mk3). Of primary interest is the 9LV 350, a command and weapon control system with electro-optical sensors and added ASW. It can engage two air targets simultaneously and, for surface engagements, it features a track-while-scan capability when using surface-to-surface missiles. The ASW subsystem can show sound path propagation data. It uses the ship sonar system for search and tracking, presents and evaluates the data, predicts the target's position, calculates the control data for the ASW weapons and calculates the ship's course. The system is designed to control ASW rockets and torpedoes but can be adapted for use with depth charges. 9LV Mk-3E is to be installed in the Swedish Visby-class stealth corvettes. [Anon, 2011]

Combat Management System	Maturity* (1)		Autonomy (3)		Performance (2)							Total Score
					Features (3)		Survivability		Weight (1)		Perf Total	
	score	total	score	total	score	total			score	total		
Combat Management System												
C-Flex	2	2	3	9	2	6	3	6	2	2	9.3	20.3
Tacticos	3	3	3	9	3	9	3	6	3	3	12.0	24.0
9LV	2	2	3	9	2	6	3	6	3	3	10.0	21.0
*for use with US systems/ships												

Figure 25. Combat Systems Software Decision Table

Decision Table Results

The three systems evaluated have all been installed and used on numerous ships and been improved through many iterations. They all have open architecture with data redundancy for survivability, and improvement in weight, footprint and usage of COTS. The ratings are fairly equal as a result.

To fully automate the ship, modifications will need to be made. Software logic will need to replace humans for fire authorization, and a proven method needs to be incorporated into the software intelligence to only target real, imminent and confirmed threat. Also, remote override of controls or remote authorization would need to be incorporated for the theater commander to make use of the ship's assets if and when necessary. Both hardware and software reliability, redundancy and recoverability need to be improved for an ideal autonomous system.

Operation with USC's will need to be incorporated into the Navy's existing methods, procedures and training.

Identification of Targets – Identification of friendly forces can be aided by current systems such as AIS (Automatic Identification System) and LRIT (Long Range Identification and Tracking system). AIS can provide unique identification, position, course, and speed. The greatest limitation of AIS is that craft under 10 tons are not required to have AIS and the small boat attack is the most likely threat when operating in the littorals. AIS can also be easily reprogrammed to ID merchant vice naval vessels. Ships outside of radio range can be tracked with LRIT with less frequent transmission. Friendly aircraft are identified using IFF.

Identification of hostiles can be done using long range video cameras similar to the ARGC-2400 long range camera, and interpretation systems such as Video Image Retrieval and Analysis Tool (VIRAT). The system can be shown a video clip of interest (in this case perhaps images of known pirate ships or pirates with guns), and it will look for similar video in the ISR imagery. It can also match a behavior of interest, given an example of the same [Peck, 2010]. With further research and higher degree of confidence, this technology could be used by a USC to effectively

identify foes. USC employment should be less data intensive since there should be a smaller set of data for known threats at sea.

Air Threat Evaluation and Weapon Choice – Aside from a gun or missile system, the ship should also be equipped with electronic support measures (ESM), electronic counter measures (ECM), chaff, and decoys. ESM, ECM, chaff and decoys can elude, confuse, and direct the attacking air threats into harmless directions or prevent an enemy from attacking. According to P. Huang and P. Kar, "The costs of operating these soft kill systems are a fraction of that for hard kill weapon systems. Replenishment of soft kill systems such as chaff and decoys can be performed easily compared with replenishing hard kill systems. In contrast, hard kill systems are expensive, difficult to maintain, and each ship can carry only a limited number of them. The cost to operate ESM and ECM is almost negligible and the resources are almost unlimited [Huang, 1994]." Huang and Kar present a coordinated AAW engagement algorithm by which the threat is assessed against defense resources to generate a set of threat/weapon pairs and selects the optimal choice based on combat doctrines and resources using standard mathematical procedures. "A combined soft kill/ hard kill engagement simulation tool that was based on Naval Research Laboratory's Full Engagement Demonstration Simulation (FEDS) model was used to test this algorithm. The results confirmed that this algorithm has potential to be used as an add-on or new development item for naval ship AAW weapon control and other resource allocation applications."

Since this is an unmanned ship with limited pre-loaded rounds, the use of decoy and chaff is a sensible option. Combat doctrines will have to be set prior to deployment or remotely communicated while underway. Doctrine will be different utilizing soft kill systems while operating independently as opposed to in close proximity to other shipping and manned naval assets.

Lethal Weapons - Existing lethal weapons (guns and missile launchers) can operate without manning, though they are normally manned for safety and ethical reasons. There are numerous CIWS which are autonomous with the exception of weapons loading. A decision table was used to compare various US and Allied models of CIWS with remote capability, with the scores

favoring those with longer range and those which are already used on US ships. The SeaRAM missile is a good choice based on those characteristics, as well as having the same footprint as the current CIWS and the future Laser weapon (LaWS). Percent kill (P_k) was not used in this comparison but should be employed in an engagement analysis before a design decision is made.

Table 18. CIWS Decision Table

Self Defense Weapon	Maturity* (1)		Autonomy (3)		Performance (2)									Total Score
					Range (3)		Firing Rate (2)		Ammo Storage (2)		Weight (1)		Perf Total	
	score	total	score	total	score	total	score	total	score	total	score	total		
Close-In-Weapon-System														
Phalanx	3	3	3	9	1	3	3	6	3	6	1	1	8	20
SeaRAM	3	3	3	9	3	9	3	6	2	4	1	1	10	22
Goalkeeper	2	2	3	9	2	6	3	6	3	6	1	1	9.5	20.5
Millennium	3	3	2	6	2	6	3	6	3	6	1	1	9.5	18.5
Typhoon	3	3	2	6	3	9	1	2	1	2	2	2	7.5	16.5
Seahawk	2	2	3	9	3	9	2	4	2	4	2	2	9.5	20.5
Rheinmetall MLG	2	2	2	6	2	6	2	4	1	2	2	2	7	15
Marlin	2	2	2	6	3	9	2	4	2	4	2	2	9.5	17.5
Narwhal	2	2	2	6	3	9	2	4	2	4	3	3	10	18
LaWS	1	1	3	9	3	9	3	6	3	6	1	1	11	21
*Maturity: usage on US Ships														

Manpower is required to load all of the above weapons (minus the laser). They can be preloaded to a certain point prior to departure and reloaded as needed, but an automated method of loading would be required for use on a USC. The AGS on DDG1000 is fully automated but is too large for a smaller USC. The ideal weapon which would not require reloading is the Laser Weapon. Various laser weapons (such as the Laser Weapon System (LaWS) or Maritime Laser Demonstration (MLD) are in development and should be ready for deployment in a couple of years. LaWS has been tested successfully in a sea environment. However, it still needs a lot of integration before becoming usable on a Navy platform as the next weapon system, and will require a huge power plant to operate, which needs to be evaluated against USC cost and needs. The table below provides an assessment of power needs.

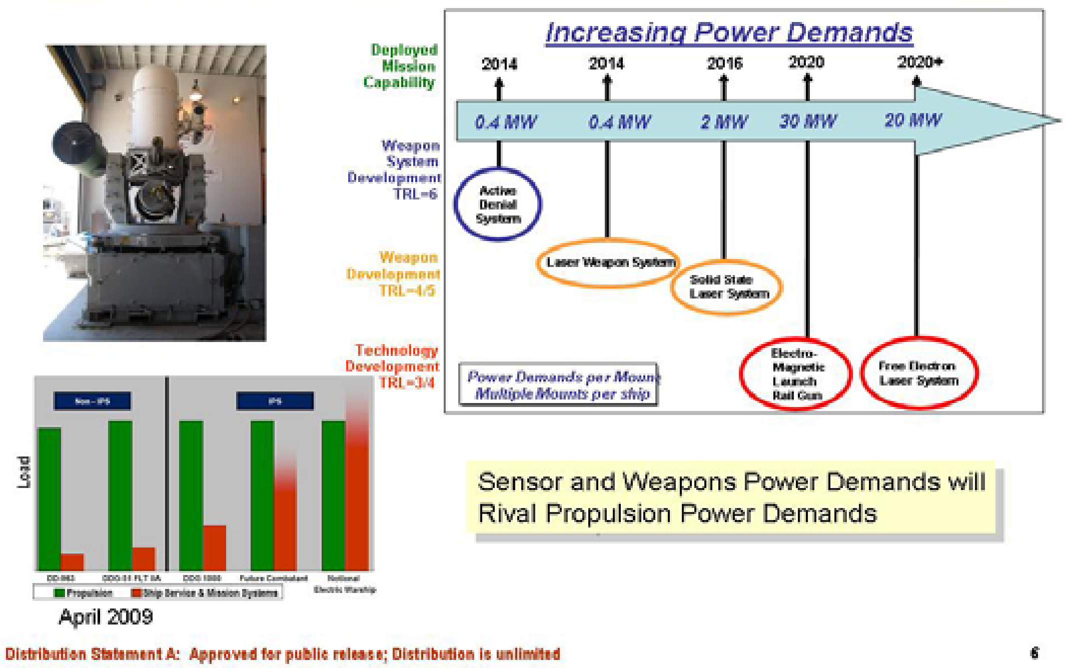


Figure 26. Power Requirements for Laser Weapon Systems [Hoffman, 2010]

Non-Lethal Weapons – There are some non-lethal weapons such as noise guns which can be adapted to a mount to enable aiming at a target (see camera example in APPENDIX F **– SELF DEFENSE TECHNOLOGIES**) with a noise or voice generator. The Long Range Acoustic Device (LRAD) is a noise gun currently used on Navy ships with a range of over 3000 meters. The device can be programmed to issue warning messages in multiple languages. The intensity of the LRAD sound waves can be adjusted to cause pain to unprotected eardrums as a non-lethal alternative. The LRAD would need to be designed to be guided and aimed by radar and sound delivery would need to be automated.

Other non-lethal weapons (such as tear gas or slippery surface sprays) and weapon detection devices (such as are used for explosive and small object detection and avoidance) would need to be used at much closer range and would have to be automated to provide further protection for the ship should hostile forces/divers attempt to board her.

6) **Damage Control**

The following damage control methods that are currently in use (or soon to be available) would provide an appropriate starting point for a notional USC:

Table 19. Damage Control Technologies

Damage Control Function	Technology
Fire Prevention	Inboard N_2 Fuel Cell Exhaust (Reduce compartment O_2 levels)
Fire Control	Water Mist and Primary Damage Area (PDA) Cooling, AFFF (spaces with fuel)
Flooding Control	Smart Valves
Damage Mitigation	Automated Damage Assessment & Decision Support Program

Fire prevention and control – Fire prevention is addressed by using Inboard N_2 Fuel Cell Exhaust. This is a very effective way to prevent a fire by reducing the oxygen level in the ship with the addition of nitrogen enriched air, which is produced by fuel cell exhaust. The N2telligence fuel cell could be used to generate the nitrogenated air, though hydrogen fuel cells are not currently in the US Navy stock. Another option would be to use the Wagner Corp method which extracts nitrogen from the outside air and feeds it into the space. Spaces would need to be sealed prior to pumping in the nitrogen, and this would be in line with normal protocol where any bulkheads are usually closed (autonomously in this case) once smoke or fire is detected. Since the ship is unmanned, low oxygen content is not a concern, and a fuel cell propulsion plant, if selected, would complement this approach. According to PC World (2007), wood stops burning when oxygen content falls to 17% and plastic cables between 16-17%. A 15 percent oxygen level is safe for humans without allowing a fire to start. This method is used by N2telligence in their patented systems for fire prevention [N2telligence, 2011].

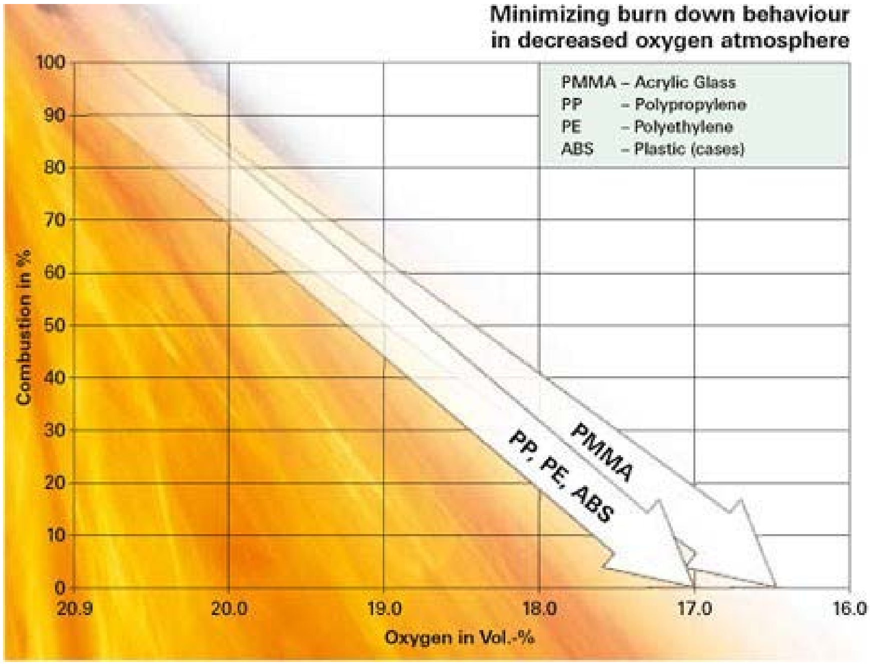


Figure 27. Burn down behavior [Wagner, 2011]

This technology is currently used by Wagner and N2telligence for data centers, but can easily be adapted for use on the USC, or at least all areas with critical equipment.

Fire detection will be automated with smoke and heat or flame detectors. Monitoring applications (cameras and backup sensors) will need to distinguish between sensors randomly failing and those being systematically destroyed by hazardous events. Fire control is addressed by the use of high pressure water mist and Primary Damage Area (PDA) systems or boundary cooling which are the latest systems used on US Navy Ships. High pressure water mist has been successfully demonstrated to snuff out fires and cool spaces in very little time, and has been installed on numerous platforms including LPD and LCS. A PDA cooling system is a bulkhead division water spray which provides cooling in each level of a watertight subdivision to prevent fire spread to other subdivisions, and is planned for installation on DDG1000. These systems are automatic and just need an adequate water source.

Flooding Control - Flooding control will be addressed by using watertight bulkheads and doors, automated dewatering pumps and automated transferring of fluids (using smart valves) to maintain ship stability. Doors can be permanently closed at ship sail away since there are no personnel onboard. Bulkhead valves will need to be automated.

Ship damage recognition and prediction – The most important aspect of unmanned damage control is restoration of the plant. Response to system damage such as broken or leaky pipes can be accomplished by the rerouting of fluids using pre-programmed smart valves. Smart valves are being used currently on the DDG 51 class starting with DDG 108 for chilled water, and on DDG 1000 for all pipe systems.

Ship damage prediction should be programmed into USC situational awareness for quicker response to damage control needs (such as starting of backup equipment or moving fuel to tanks opposite of possible flooding zone). When an attack is encountered, the software would compute weapon attack (incoming missile) coordinates, calculate possible damage, flooding and fire spread zones, and determine appropriate response or dynamic preparation [Hou, 2010]. This software is not a mature technology but should be ready for a 2020 IOC if it is invested in now. Inbound missiles tracking has already been included in self defense considerations.

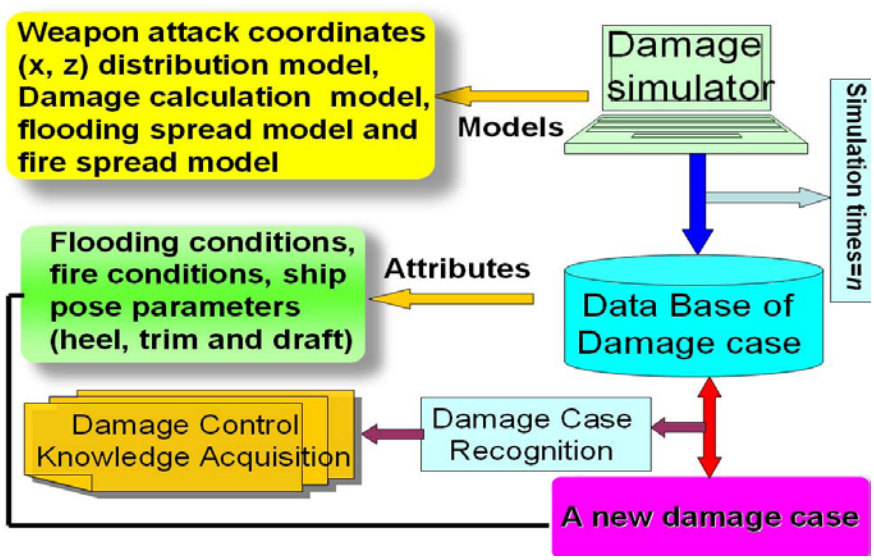


Figure 28. Structure of ship damage case recognition subsystem [Hou, 2010:3405]

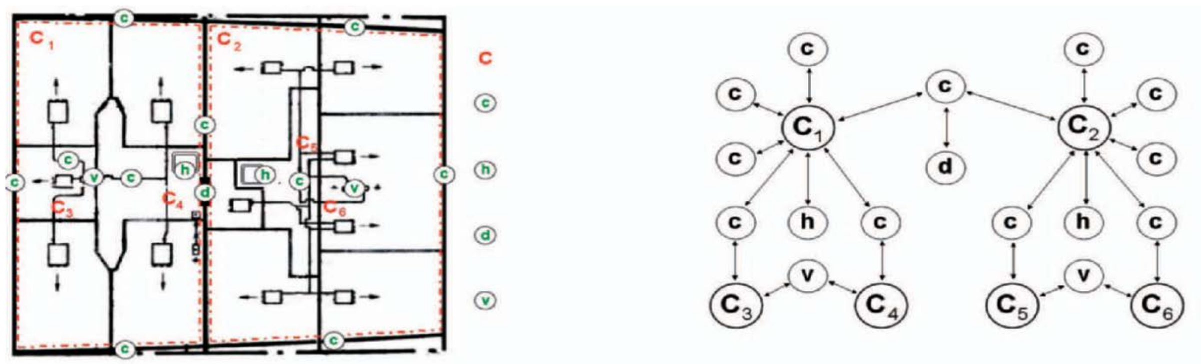


Figure 29. Damage Assessment/Decision Support Program [Varela, 2007:60]

Figure 29 shows a simplified compartment and ventilation arrangement in a military ship, with containers and connectors identified.   Logic is programmed for automated control (closure) of these nodes based on the specific damage situation in order to stop progressive fire or flooding.

It is important that adequate sensors are in the prediction/monitoring systems to record timely equipment health status, and that IR cameras are mounted in strategic locations so that, if needed, remote operators can see damage areas in order to assess the ship's capabilities and intervene effectively. Sensor data which should be recorded on the USC includes operating temperatures, fluid levels, differential pressure, flow, vibration, particle counter, stress levels, etc. to enable the ship to do self-diagnosis, take automated corrective action if available, and provide accurate information to remote operators.

Power Management – An automated optimal network configuration that restores the power system network without violating power system operating constraints should be implemented on the USC to enable the ship to remain operational after a casualty. Some development to date uses dynamic formulation and a static implementation of a new damage control method at the DC zonal integrated fight through power system level. Current research involves developing a dynamic implementation of the damage control method. Researchers at the Power System Automation Laboratory (PSAL) at Texas A&M University are developing dynamic solutions for various power management functions, including damage control, to implement on Next Generation Integrated Power System (NGIPS) Shipboard Power Systems [Amba, 2009].

Under Hull Monitoring – Under hull monitoring can be accomplished using available sonar or an AUV such as Cetus II with a Miris Sonar or a Hovering Autonomous Underwater Vehicle (HAUV) in remote mode via a tether [Anon, 2011]. Launch and recovery of this vehicle will need to be included in the USC design for operation especially while in hostile ports, and may be able to service both hull monitoring and MIW.

Intrusion Control - Security at the pier, if necessary, can be augmented using cameras and facial recognition technology such as is used at airports for screening of potential suspects/terrorists in foreign ports. 2D images work better under low lighting conditions and this method is less expensive than 3D. One such system is Smartgate.

Gangways would be remotely operated by maintenance crew as needed. All access doors can be cipher locked or smart card accessed and protected with alarms and non-lethal weapon sprays

such as tear gas, should a confirmed intrusion attempt be made. Museum style security can be used in secured spaces. Once a breach occurs of a secured area, possible use of lethal weapons may be considered, or equipment/data self destruction.

C. NOTIONAL CONCEPT

The USC notional concept is a possible ship configuration based on the constraints, considerations, and relevant technologies that allow an unmanned autonomous USC to perform the primary missions of MIW and ASW. Table 21 summarizes the technologies, systems and characteristics chosen for the USC.

Table 20. USC NOTIONAL CONCEPT DESCRIPTION AND TECHNOLOGIES

INITIAL OPERATIONAL CAPABILITY		2020	**Modification Level Required For Full Autonomy**	
SPEED		30 Knots		
RANGE		4500 nm @ cruising speed		
CREW SIZE		0 Officers, 0 Enlisted	**Hardware**	**Software**
	Length	250 -300 ft.	N/A	N/A
	Beam	40 - 60 ft.	N/A	N/A
	Draft	10 - 15 ft.	N/A	N/A
HULL	Hull form	Glass Reinforced Plastic Monohull	N/A	N/A
	Propulsion	Podded Electric Propulsor		
	Power Plant	Fuel Cell		
MACHINERY	Auxiliary Systems	Modular Design		
	Mine Hunting	ALMDS		
	Mine Neutralization	Archerfish		
MINE WARFARE	Mine Sweeping	Unmanned Surface Sweep System (US3)		
	Hull Mounted Sonar	Ultra ISS - HMS		
	Towed Sonar	Ultra ISS - VDS		
ANTI-SUBMARINE	Sonobuoys	Ultra ISS - Sonobuoys		
WARFARE	Torpedo	Mk 54 Lightweight Hybrid		
NAVIGATION		Autonomous Maritime Navigation (AMN) System		
	Fire Prevention	Inboard N_2 Fuel Cell Exhaust (Reduce compartment O_2 levels)		
	Fire Control	Mist and Primary Damage Area (PDA) Cooling		
	Flooding Control	Smart Valves		
DAMAGE CONTROL	Damage Mitigation	Automated Damage Assessment & Decision Support Program		
	Ship Control System	Central Computing Control Computer		
	C2	GCCS - Maritime		
USC CONTROL	External Communications	UHF LOS, Ku-band, Ku-band SATCOM, L-band LOS, L-band SATCOM, S-band		
	Weapons Control	Tacticos		
	Electronic Warfare	SEWIP		
	Decoy	MK-53 Nulka		
	Missile	SeaRAM		
ECM / SELF DEFENSE	Gun	Bofors		

Legend

Green - Requires Minimal Design Modifications

Yellow - Requires Moderate Design Modifications

Red - Requires Significant Design Modifications

Some of these capabilities will be accomplished by systems that are ready for inclusion into the USC while others require moderate to significant development. These technologies, systems and characteristics were identified as the best alternatives that are currently available or development is estimated to be complete to meet the 2020 IOC date. Additionally, each of these technologies has been assigned a color code that indicated the amount of modification required for full autonomy. The modification level has been divided into a hardware and software category to further refine the level of work necessary to make the system or function fully autonomous.

D. SUGGESTED CONCEPT ALTERNATIVES

The notional USC concept technologies and systems presented earlier were suggested based on a number of factors including maturity, autonomy, and performance. Autonomy was weighted the highest since the main purpose of the project was to investigate an unmanned surface combatant, and the other factors were weighted less heavily. That said, Navy developers may have other competing priorities which would change weighting factors and potentially result in different baseline technologies for a USC. An attempt was made to look at some of these trade-offs in the categories of cost and technical performance in order to more thoroughly understand the problem and further explore the potential solution space. These constraints were thought to have significant impact on the USC's capabilities, and they were varied in order to produce a low cost and a high performance alternative.

Low Cost Alternative

Development of the suggested baseline USC technologies requires a significant budget, which may not be supportable in a declining economic environment. The preferred notional concept is expected to be a multi-mission combatant fully capable of operating with a Strike Group and performing independent missions. The low cost alternative would be a reduced capability combatant that would be built with less expensive materials and systems, and might trade off large numbers of missiles in favor of cheaper weapons such as chaff and decoys. The systems which changed based on the cost evaluation are highlighted in the following table:

Table 21: Low Cost Alternative

INITIAL OPERATIONAL CAPABILITY		2020
SPEED		30 Knots
RANGE		4500 nm @ cruising speed
CREW SIZE		0 Officers, 0 Enlisted
	Length	250 -300 ft.
	Beam	40 - 60 ft.
	Draft	10 - 15 ft.
HULL	Hull form	Steel Monohull
	Propulsion	Controllable Pitch Propellor
	Power Plant	Diesel Engine
MACHINERY	Auxiliary Systems	Modular Design
	Mine Hunting	AN/AQS-20
	Mine Neutralization	Archerfish
MINE WARFARE	Mine Sweeping	Unmanned Surface Sweep System (US3)
	Hull Mounted Sonar	Ultra
	Towed Sonar	None
ANTI-SUBMARINE WARFARE	Torpedo	Mk 54 Lightweight Hybrid
NAVIGATION		Autonomous Maritime Navigation (AMN) System
	Fire Prevention	Inboard N_2 Fuel Cell Exhaust (Reduce compartment O_2 levels)
	Fire Control	Mist and Primary Damage Area (PDA) Cooling
	Flooding Control	Smart Valves
DAMAGE CONTROL	Damage Mitigation	Automated Damage Assessment & Decision Support Program
	Ship Control System	Central Computing Control Computer
	C2	GCCS - Maritime
USC CONTROL	External Communications	UHF LOS, Ku-band, Ku-band SATCOM, L-band LOS, L-band SATCOM, S-band
	Weapons Control	C-Flex
	Electronic Warfare	SEWIP
	Decoy	MK-53 Nulka
	Missile	SeaRAM
ECM / SELF DEFENSE	Gun	Bofors

High Performance Alternative

The suggested notional concept was selected with systems that were capable of adequately performing their intended function, and with systems that were able to be automated for inclusion in the USC. The high performance alternative would include the systems that were capable of significantly increased performance regardless of investment. Some technologies which would be very beneficial for the USC had been ruled out prior to development of the decision tables due to very immature technology or lack of information about the systems. Therefore, the team approach to the high performance alternative was to interview the team researchers in each area and list the best technologies which could enhance USC performance. These technologies are highlighted in

Table **23** and some additional thoughts are described in more depth below:

- Some general thoughts on a craft with significantly increased performance would be to design a unique hull form specifically suited for ASW and MIW missions, as well as increased weapons for ASW and self defense missions.
- A MIW system which can detect, classify, identify and engage all in one pass is in the very early stages of development – this would be the best performing system because it would take the least amount of time.
- A laser gun with updated electric plant was favored instead of the SeaRAM for the close in weapons system. This system requires more power than the SeaRAM but should be available by 2020 and fits in the current CIWS mount.

Table 22: High Performance Alternative

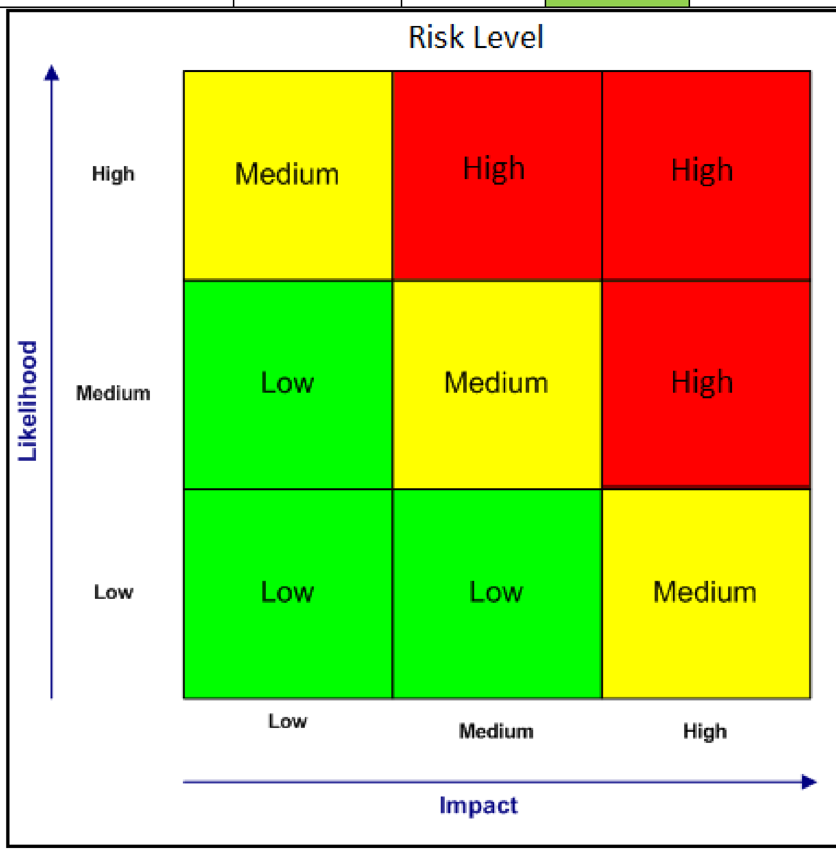
INITIAL OPERATIONAL CAPABILITY		2020
SPEED		30 Knots
RANGE		4500 nm @ cruising speed
CREW SIZE		0 Officers, 0 Enlisted
	Length	250 -300 ft.
	Beam	40 - 60 ft.
	Draft	10 - 15 ft.
HULL	Hull form	Glass Reinforced Plastic Monohull
	Propulsion	Podded Electric Propulser
	Power Plant	Fuel Cell
MACHINERY	Auxiliary Systems	Modular Design
	Mine Hunting	All-in-one hunting and neutralization package
	Mine Neutralization	
MINE WARFARE	Mine Sweeping	Unmanned Surface Sweep System (US3)
	Hull Mounted Sonar	Ultra
	Towed Sonar	ISS - VDS
ANTI-SUBMARINE WARFARE	Torpedo	MU90 IMPACT
NAVIGATION		Autonomous Maritime Navigation (AMN) System
	Fire Prevention	Inboard N_2 Fuel Cell Exhaust (Reduce compartment O_2 levels)
	Fire Control	Mist and Primary Damage Area (PDA) Cooling
	Flooding Control	Smart Valves
DAMAGE CONTROL	Damage Mitigation	Automated Damage Assessment & Decision Support Program
	Ship Control System	Central Computing Control Computer
	C2	GCCS - Maritime
USC CONTROL	External Communications	UHF LOS, Ku-band, Ku-band SATCOM, L-band LOS, L-band SATCOM, S-band
	Weapons Control	Tacticos
	Electronic Warfare	SEWIP
	Decoy	MK-53 Nulka
	Missile	Laser Weapon (LaWS)
ECM / SELF DEFENSE	Gun	Bofors

APPENDIX I – RISK ASSESSMENT

No.	Risk	Likelihood	Impact	Risk Level	Mitigation Strategy
1.0	DESIGN PHASE				
1.1	System components cannot be modified for full autonomy	Medium	Medium	Medium	Investigate alternative tech option. Consider redesign to allow autonomous operation
1.2	Systems are not sufficiently redundant	Low	Medium	Low	Redesign to allow for sufficient redundancy
1.3	Systems are not sufficiently distributed	Low	Medium	Low	Redesign to allow for sufficient system distribution
1.4	Systems chosen are insufficient to meet requirements	Low	Medium	Low	Investigate alternative system or system of systems to meet requirements. Or seek reduction in system requirements
1.5	System cost exceeds estimates	Medium	Low	Low	Use conservative methods for cost estimation especially when cost data is not current, accurate, and representative
2.0	ACQUISITION PHASE				
2.1	Sub-systems do not integrate with USC system	Medium	High	High	Allow for extended programming time to ensure proper system integration
2.2	System components do not interoperate with one another	Medium	High	High	Allow for extended programming time and testing to ensure interoperability
2.3	C3 programming is more extensive and complex than planned	Medium	High	High	Allow for extended programming time and testing to ensure adequate C3 programming
2.4	C3 programming is	Medium	High	High	Allow for extended programming

	insufficient				time and testing to ensure adequate C3 programming
2.5	Composite Hull size too large for industry	Medium	Low	Low	Allow for extended manufacturing time to build hull to design size
3.0	OPERATIONAL PHASE				
3.1	USC loses communications w/ command	Medium	High	High	Build in fail-safe return to base program if system communication is lost for X amount of time
3.2	USC cannot process data/processes data incorrectly (program testing insufficient)	Medium	High	High	Develop a multitude of system tests to ensure system can process data received by sensors correctly. Identify basic actions for USC to take when data is conflicting
3.3	Data rate too fast for USC to cope	Low	Medium	Low	Implement data reduction techniques for data transmission. Implement "safe mode" of data gathering and processing when data overload occurs. Add programming for data read while writing capability and data interpolation should segments of data become corrupted
3.4	Incorrect IFF and subsequent action	Low	High	Medium	Thorough programming and testing of IFF and lethal weapon use. Have two systems independently process the data and fire only when analysis matches. Limit lethal weapons to human operator override for all non defensive uses
3.4	Insufficient recovery after failure or damage	Medium	Medium	Medium	Ensure systems are as distributed as possible. Additional testing of damage scenarios to ensure

					recovery ability
3.5	Issue with refueling while underway	Low	Medium	Low	Thorough refueling concept development and testing. Plan for refueling at non-emergency level to allow USC to travel towards a depot if unsuccessful refueling underway. Incorporate tow cables into design if USC runs out of fuel while underway



Risk Matrix

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